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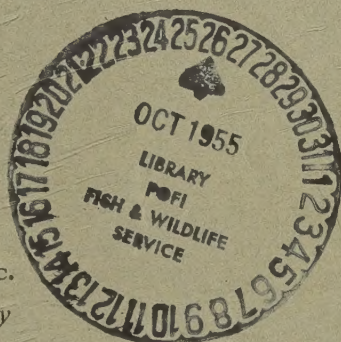
NO. 8

Physical Oceanography of the Irish Sea

BY

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*Department of Oceanography
The University of Liverpool*



LONDON: HER MAJESTY'S STATIONERY OFFICE
1955

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OF THE
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PHYSICAL OCEANOGRAPHY OF THE IRISH SEA

I. INTRODUCTION

THE term "Irish Sea" will be taken to include the whole sea area from the North Channel southwards to a line from Cape Clear to Land's End (see Fig. 1). So defined, the Irish Sea is, roughly, a funnel-shaped body of water communicating with the Atlantic Ocean at both ends. It is bounded on the west by the east and south coasts of Ireland, and on the east by the south-west coast of Scotland and the west coasts of England and Wales.

The southern entrance is wide, about 170 sea miles from Cape Clear to Lands End, but north of the Bristol Channel the Sea narrows to 42 sea miles between Carnsore Point and St. Davids Head, remaining fairly narrow in St. George's Channel and as far north as the Dublin-Holyhead line. North of this it widens out into a broad expanse, about 105 miles wide and 80 miles long, with the Isle of Man in the middle. Then it closes in to the North Channel, which is 20 sea miles wide between north-east Ireland and the Galloway peninsula. Beyond this it is joined by the Firth of Clyde, and the combined waters communicate with the Atlantic Ocean through the channel, 11 sea miles in width, between Torr Point (Antrim) and the Mull of Kintyre. The total length of the Irish Sea, along the axis of the main channel, is about 275 sea miles.

The whole of the Irish Sea is comparatively shallow. Across the southern entrance the general depth is 50–60 fathoms, and a channel deeper than 50 fm. extends northwards into St. George's Channel. On either side, there are broad areas with shallower depths; from 30–50 fm. south of Ireland and less than 40 fm. in the Bristol Channel. On the west side of St. George's Channel, 4–6 miles from the Irish coast, there is a series of banks reaching nearly to the surface. The deep channel, with depth nowhere less than 45 fm., can be traced northwards through the Sea and out through the North Channel. It passes to the west of the Isle of Man, and the north-east part of the Irish Sea—east of a line from the Mull of Galloway to Holyhead—is shallow, mostly less than 30 fm. Between the east coast of the Isle of Man and the English coast the average depth is only 15 fm. Off the north-west coast of England, large areas of sandbanks are exposed at low tide, particularly in the Solway Firth, Morecambe Bay, and the estuaries of the Ribble, Mersey, and Dee. The deepest part of the Irish Sea is found in the North Channel, off Galloway, where a narrow trough extends to a depth of nearly 150 fm.

Being so largely surrounded by land, the Irish Sea receives the run-off from a large drainage area, the total catchment area being about 35,800 sq. miles, compared with about 38,500 sq. miles, which is the area of the Sea itself. The considerable influence of the surrounding land on physical conditions in the Irish Sea will be seen repeatedly in the ensuing survey.

II. TEMPERATURE

I. Observations

The temperature observations on which this account is based have been made at various times since 1900, and fall into two main classes: (A) those in which the temperature was measured at various sub-surface depths as well as at the surface, and (B) surface observations only. The positions of stations at which regular observations of temperature have been made are shown in Fig. 2 (page 7).

(A) *Observations at Various Depths*

Between 1903 and 1914, the Fisheries Branch of the Department of Agriculture and Technical Instruction for Ireland organized quarterly cruises by the s.s. *HELGA*, on which temperature observations were made at the surface and at a number of depths. Thirty-nine stations, distributed over the Irish Sea, including the Southern Entrance, were visited regularly on these cruises. Samples were taken by Ekman reversing water-bottle, and the temperatures read to 0.01°C.

In 1920 the *HELGA*, later renamed the *MUIRCHU*, began another series of cruises, and quarterly observations were made at a number of stations in the Southern Entrance until 1936.



1. Irish Sea : bottom contours and boundaries of catchment areas

- Boundaries of catchment areas draining to the Irish Sea
- - - - - sections dividing Irish Sea into three regions



Between 1907 and 1914, observations at various depths were made at a number of stations in the north-east part of the Irish Sea on regular cruises by the s.s. JAMES FLETCHER, the patrol vessel of the Lancashire and Western Sea Fisheries Committee. The samples were taken by Nansen-Pettersson insulating water-bottle and the temperatures read, sometimes to 0.01°C ., and at other times to 0.1°C . These cruises were carried out quarterly at first, and then monthly from May, 1910, until the outbreak of World War I.

The Marine Biological Association organized quarterly cruises, carried out by the s.s. HUXLEY, during which observations at various depths were made at several stations in the Southern Entrance from 1907 to 1909. The Nansen-Pettersson water-bottle was used.

Charts of mean values of surface and bottom temperatures were published by Matthews in 1910, based on the observations up to that date. He showed that in the winter months the temperature is practically uniform from surface to bottom throughout the whole Sea. In summer there is a marked difference between the Southern Entrance, where a pronounced thermocline develops, and the rest of the Irish Sea, where the temperature at the surface does not exceed that at the bottom by more than a few tenths of a degree centigrade. There are two exceptions to this generalization: (1) the deep area between the Isle of Man and Ireland, where the tidal streams are weak, and (2) the shallow areas off the coast of north-west England.

Over the greater part of the area referred to, however, observations of surface temperature may be taken as representing the temperature from surface to bottom at all seasons. This circumstance gives added value to the large number of observations of surface temperature which have been made in the main part of the Irish Sea.

(B) Surface Observations Only

At Port Erin Bay, Isle of Man, the surface temperature has been measured twice daily, at 9 a.m. and 4 p.m., from 1902 up to the present day. The observations have been made by the staff of the Marine Biological Station there, the thermometers being read to 0.5°F .

At a number of lightvessels, temperatures were recorded twice daily for the Meteorological Office, the measurements being made "at or about sunrise" and at 4 p.m., and read to 1°F . The total periods covered by the observations varied from station to station, partly due to movements of the lightvessels, but were mostly between 1904 and 1918. From Caernarvon Bay L.V., however, a continuous series of observations from 1907 to 1926 was obtained. The Irish Fisheries Branch arranged for observations at approximately weekly intervals from three lightvessels off the east coast of Ireland and the Fastnet lighthouse.

In addition to the quarterly cruises mentioned under Section (A) (page 5) the Lancashire and Western Sea Fisheries Committee collected measurements of surface temperature at frequent, but irregular, intervals from a number of positions near the coasts of north-west England and Wales. Most of these observations were made from the patrol vessel, when the thermometers were read to 0.1°C ., but some were made by the Bailiffs' launches, using thermometers read to 1°F .

Between 1922 and 1925, surface observations on two consecutive days each month were made at four stations on the Holyhead-Dublin steamer route and at several stations on the Fishguard-Rosslare route. This work was organized by the Ministry of Agriculture and Fisheries, and the thermometers read to 0.1°C . A second series of observations on the Holyhead-Dublin route was arranged by the Oceanography Department, University of Liverpool, was made from 1926 to 1928 and from 1928 to 1931 the Department of Lands and Fisheries for Ireland organized similar observations on the Lands End-Dublin and Lands End-Cork routes.

From 1934 up to the present time, the Oceanography Department of the University of Liverpool has organized regular observations of surface temperature at nine stations, from lightvessels, light-houses, and steamer routes. These observations have been made three times weekly and the thermometers read to 0.1°C .

The above description of sources of observations is not exhaustive. Further details and references to the publication of the original data have been given by Proudman, Lewis, and Denham (1937), who published an account of "The temperature of the surface waters of the Irish Sea" making use of all data collected between 1900 and 1934. In the present account, much use has been

de of this paper, supplemented by the data obtained between 1934 and 1946, which has been analysed by Gilles (1949). For the Southern Entrance, data on temperature at various depths have been taken from Matthews (1913) and from the later work by the s.s. MUIRCHU, from which mean values have been deduced previously (Bowden, 1950).

Charts of Mean Values

In deriving mean values, the procedure of Proudman, Lewis, and Dennis (1937) has been followed. The term "particular mean value" denotes an average value over a particular calendar month or year. A "grand mean value" (or long-period mean) denotes an average value of the particular mean values over a period of years. From the grand mean values for each station for a period of observations there, Proudman, Lewis, and Dennis inferred grand mean values for a common period, 1903-31. To do this, use was made of the correlation between the particular monthly mean values at the station in question and at Port Erin Bay, which was regarded as the standard station for this purpose. This common period has been retained in the present work, for the purpose of drawing charts, the later data being corrected by the same method. However, all the information given in Tables 1, 2 and 3 (pages 21-23) is based on grand mean values for the actual period of observations at each station.

The charts in Figs. 3(a)-3(e) (pages 10-14) show the mean positions of the surface isotherms for the year as a whole and for the months of February, May, August, and November. Figs. 4(a)-4(e) (pages 15-19) show the bottom isotherms for the Southern Entrance only. The charts are largely self-explanatory, but the following notes on them may be helpful.

Surface Temperatures

The mean annual temperature in the main channel of the Irish Sea decreases from 12.0°C. in the Southern Entrance to 10.0°C. in the North Channel. It also decreases from the centre of the channel towards the sides, so that along most of the east coast of Ireland it is less than 10.5°C., while on the English side it becomes less than 10.0°C. in the upper part of the Solway Firth, in Morecambe Bay, and the Ribble estuary.

In February, the temperature following the main channel decreases from a little over 9.0°C. in the Southern Entrance to between 7.0°C. and 7.5°C. in the North Channel. Towards the sides the temperature decreases considerably, the isotherms running practically north and south near the coasts. Along the whole of the east coast of Ireland the temperature is less than 7.0°C., it is less than 5.0°C. along the English coast from the Solway to the Dee, and about 6.0°C. near the east of Cardigan Bay in Wales.

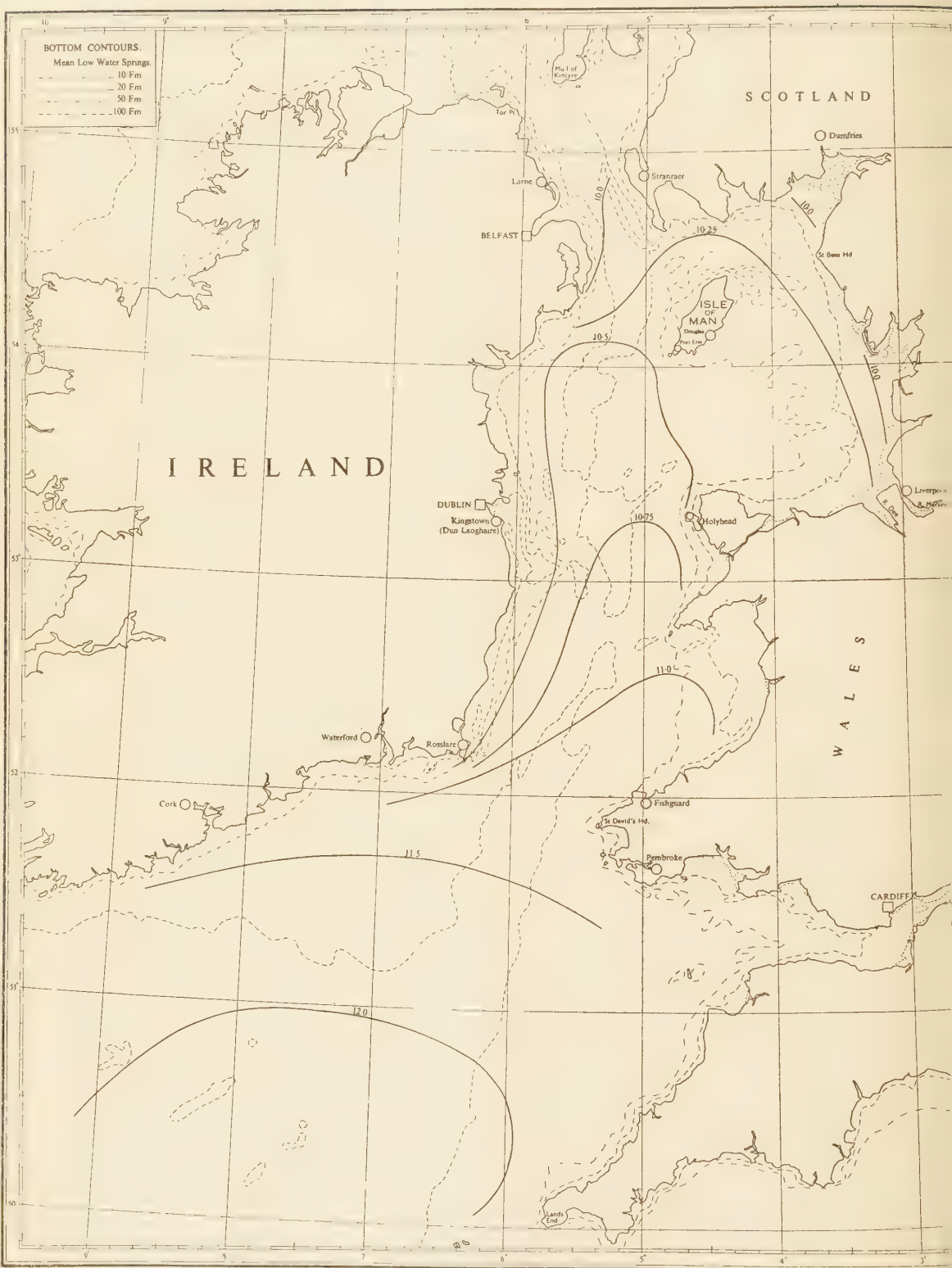
In May the temperature of the whole region is naturally higher, decreasing from 11.0°C. across the Southern Entrance to less than 8.5°C. in the North Channel. In contrast to the February conditions, the temperature now increases towards the coasts, but not to a great extent.

The surface temperature in August is considerably higher, especially in the Southern Entrance where it reaches 16.5°C. in the extreme south of the area. It decreases to 14.0°C. in St. George's Channel and is then fairly uniform in the main fairway, becoming less than 13.0°C. in the North Channel. Towards the coasts the temperature increases, particularly on the east side. Off Ireland does not reach much above 14.0°C., but on the east side it exceeds 16.0°C. in the shallow waters of the north-west coast of England, and in the inner part of Cardigan Bay.

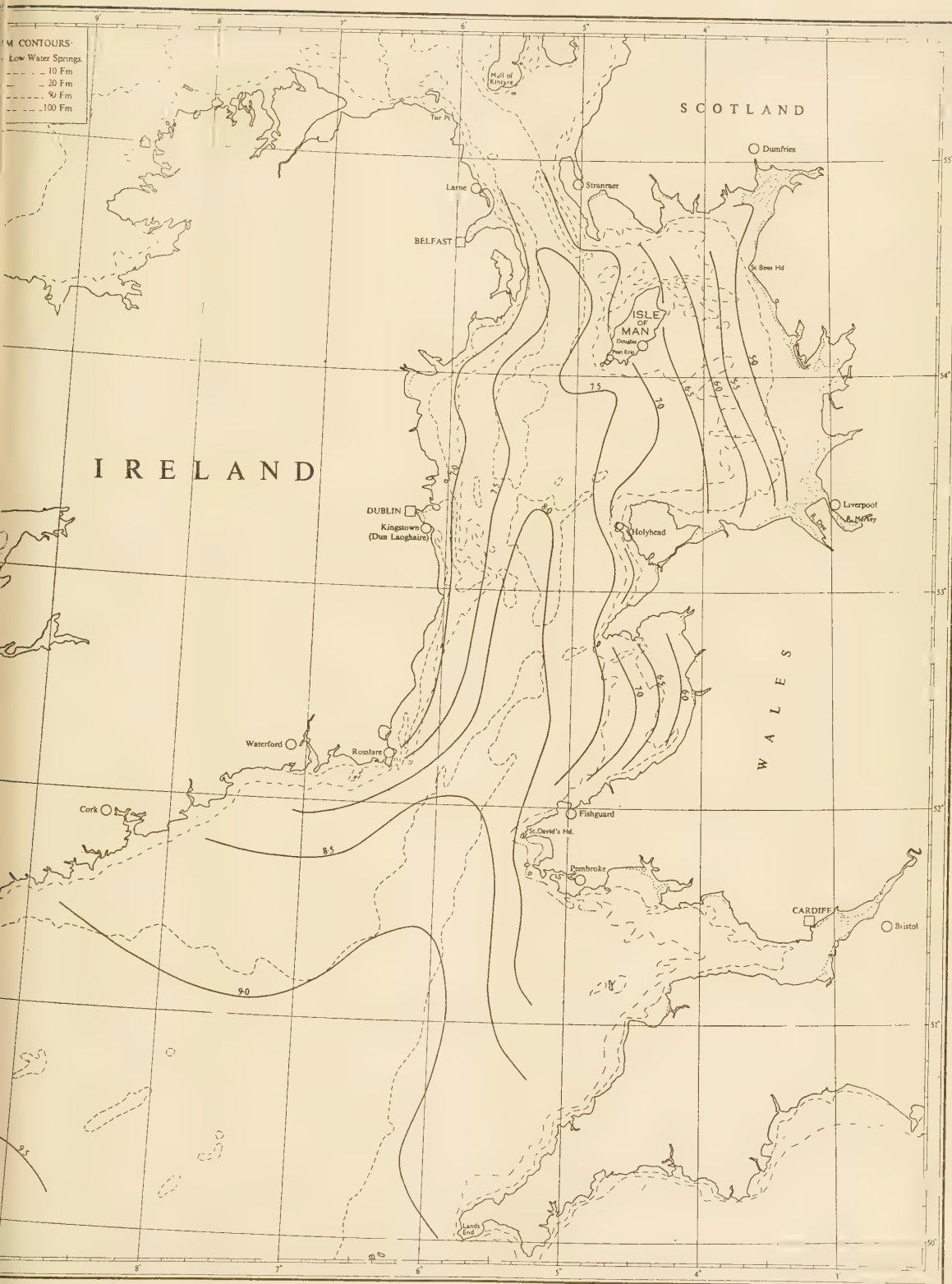
In November the isotherms tend to run north and south. Across the Southern Entrance the temperature increases from less than 11.0°C. in the west to over 13.0°C. across the entrance to the Bristol Channel. North of St. George's Channel a tongue of water with temperature greater than 10.0°C. extends almost to the North Channel. The temperature decreases towards the coasts, the change again being more marked on the east side, where temperatures less than 8.0°C. occur in the Solway Firth and from Morecambe Bay to the Dee estuary.

Bottom Temperature between the Isle of Man and Ireland

In a region extending from the North Channel southwards to latitude about 53° 40'N and from the coast of Ireland to longitude about 5° 00'W, Matthews's investigations showed that appreciable temperature layering occurs in the summer months. In February the temperature is practically constant from surface to bottom, and in May the difference does not exceed 1.0°C.



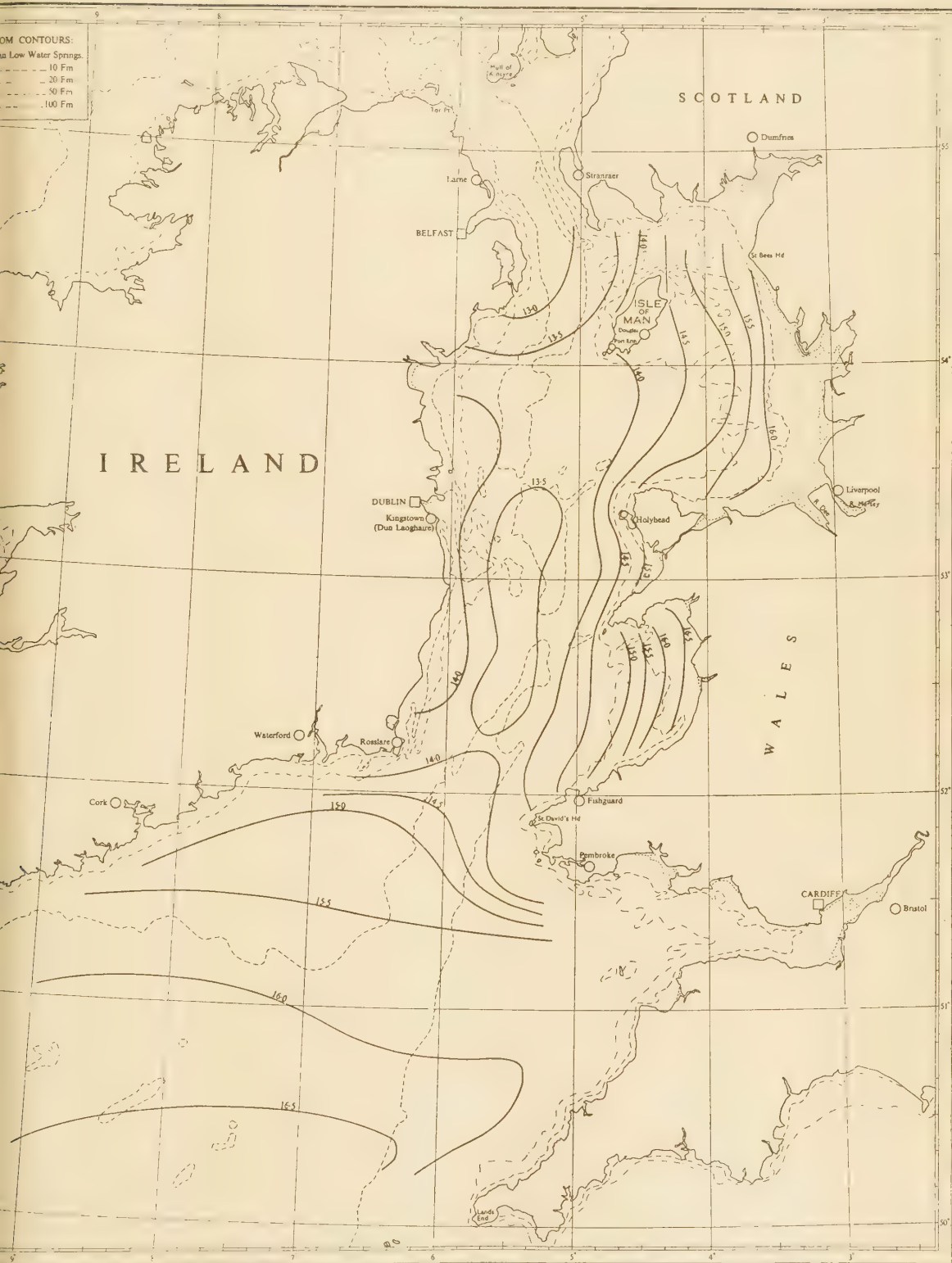
3 (a). Irish Sea : surface temperature—Year



3 (b). Irish Sea : surface temperature—February



3 (c). Irish Sea : surface temperature—May



Ordnance Survey 1953.

3 (d). Irish Sea : surface temperature—August



3 (e). Irish Sea : surface temperature—November



4 (a). Irish Sea : bottom temperature in the Southern Entrance—Year





4 (d). Irish Sea : bottom temperature in the Southern Entrance—August

Ordnance



Ordnance Survey

4 (e). Irish Sea : bottom temperature in the Southern Entrance—November

In August, however, the surface temperature is higher than that at the bottom by about 1·6°C. in the section from Skulmartin to Mull of Galloway, and by up to 4°C. in a section in latitude 53° 40'N. Vertical uniformity has been re-established by November.

Temperature layering occurs to a small extent in the shallow areas off the north-west coast of England, as found by the Lancashire and Western Sea Fisheries Committee's investigations.

Bottom Temperature in the Southern Entrance

The mean annual temperature is about 2°C. lower at the bottom than at the surface. Over most of the Southern Entrance the bottom temperature is between 9·0°C. and 10·0°C., with an area of minimum in the centre, the increase of temperature being especially marked towards the mouth of the Bristol Channel.

In February the surface and bottom temperatures are practically identical.

By May the surface and bottom isotherms have separated. While the surface temperature has risen by 1·5°C. to 2·0°C., the bottom temperature has remained practically unchanged since February. In a region in the deepest part of the channel it has actually decreased.

In August the difference between surface and bottom is more pronounced, the surface temperature being up to 6°C. higher than the bottom temperature. The bottom temperature still shows an area of minimum (less than 9°C.) in the centre of the Southern Entrance, with the temperature increasing outwards, especially towards the east.

In November, the distribution of bottom temperature is still characterized by an area of minimum, but the bottom temperature has continued to rise and has now reached its maximum.

3. Mean Values at Representative Stations

Table 1 (page 21) gives grand mean values of surface temperature for each month and for the year for thirteen representative stations in the Irish Sea. The positions of these stations and the periods covered by the observations, from which the mean values are derived are :

Stations	Latitude, N	Longitude, W	Period of Observations
Stranraer-Larne, halfway	54 57	5 28	Mar. 1935 to Dec. 1946
SOLWAY L.V.	54 48	3 32	Jan. 1907 to July 1918
BAHAMA BANK L.V.	54 20	4 13	Jan. 1907 to June 1915
Port Erin Bay	54 05	4 46	Jan. 1903 to Dec. 1946
MORECAMBE BAY L.V.	53 54	3 31	Jan. 1935 to Dec. 1946
LIVERPOOL BAR L.V.	53 32	3 18	„ „
Near Holyhead	53 20	4 44	„ „
Holyhead-Kish, halfway	53 20	5 16	„ „
Near Kish	53 19	5 52	„ „
Bardsey L.H.	52 45	4 48	„ „
Fishguard-Rosslare, halfway	52 08	5 40	May 1934 to May 1941
CONINGBEG L.V.	52 02	6 40	Jan. 1904 to Apr. 1915
SEVEN STONES L.V.	50 03	6 04	Jan. 1903 to Dec. 1931

The positions of the stations are shown in Fig. 2 (page 7).

TABLE 1
Grand Mean Values of Sea Surface Temperature at Representative Stations in °C.

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Period
Stranraer-Larne ..	8.15	7.16	6.71	7.31	8.58	10.46	12.26	13.20	13.40	12.74	11.38	9.60	10.08	1935-46
SOLWAY L.V.	4.85	4.73	5.33	7.20	10.40	13.53	15.49	15.77	13.94	11.21	7.57	5.48	9.65	1907-18
BAHAMA BANK L.V. ..	6.83	6.13	6.36	7.38	9.58	11.96	13.86	14.88	14.54	13.11	10.43	8.45	10.32	1907-15
Port Erin Bay ..	8.07	7.15	7.00	7.82	9.25	11.38	13.17	14.05	13.73	12.56	10.86	9.40	10.37	1903-51
MORECAMBE BAY L.V.	5.78	4.99	5.55	7.64	10.46	13.69	15.93	16.61	15.63	13.05	9.99	7.36	10.56	1935-46
LIVERPOOL BAR L.V. ...	5.48	5.00	5.56	8.01	10.83	14.22	16.40	17.07	15.59	12.67	9.48	6.93	10.61	1935-46
Holyhead	7.87	7.33	6.98	8.12	9.50	11.67	13.56	14.87	14.78	13.43	11.37	9.38	10.74	1935-46
Holyhead-Kish ..	8.96	8.17	7.70	8.14	9.13	11.00	12.63	13.75	14.08	13.46	12.03	10.42	10.79	1935-46
Kish	8.34	7.59	7.28	8.13	9.63	11.63	13.22	14.28	13.89	12.95	11.42	9.85	10.68	1935-46
Bardsey L.H.	8.40	7.65	7.66	8.71	10.21	12.20	14.03	15.11	15.08	13.67	11.65	9.83	11.18	1935-46
Fishguard-Rosslare ..	9.50	8.35	7.77	8.03	9.11	10.89	13.28	14.23	14.51	13.56	12.26	10.76	11.02	1935-41
CONINGBEG L.V. ..	8.56 8.69	7.93 8.17	7.73 8.04	8.35 8.74	9.77 10.11	11.63 11.94	13.09 13.41	14.05 14.36	14.07 14.47	13.38 13.52	11.47 11.69	9.67 9.99	10.81 11.09	1904-15 1925-47
SEVEN STONES L.V. ...	10.05 10.50	9.49 9.80	9.23 9.60	9.67 10.08	10.85 11.02	13.03 13.40	15.15 15.42	15.83 16.60	14.87 15.92	13.45 14.30	12.04 12.90	10.94 11.56	12.05 12.61	1903-38 1947-51

Table 2 gives mean values of temperature at various depths at three representative stations in the Southern Entrance for the months of February, May, August and November.

TABLE 2
Mean Values of Sea Temperature at Various Depths, at Three Stations in the Southern Entrance
(Observations taken between 1920 and 1936)

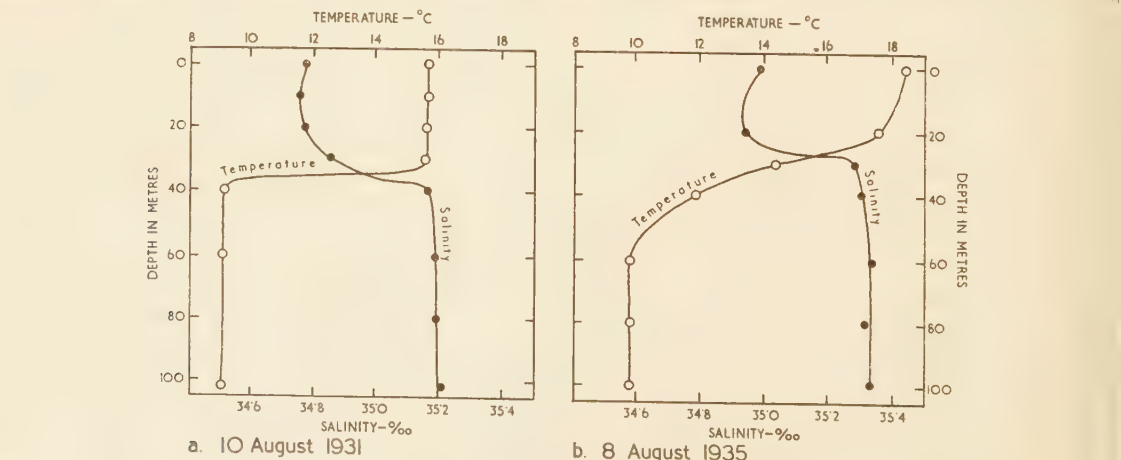
Depth (m.)	A. 51° 40'N, 8° 00'W				C. 51° 00'N, 8° 00'W				E. 50° 20'N, 8° 00'W			
	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.
0	8.56	10.57	15.21	11.06	9.20	10.92	16.05	11.72	9.30	11.44	16.69	11.94
20	8.60	10.13	14.50	11.13	9.14	10.63	15.40	11.72	9.28	10.81	16.30	11.95
40	8.64	9.12	11.11	11.12	9.14	9.74	10.66	11.39	9.30	11.00	11.26	11.95
60	8.72	8.80	10.30	10.83	9.13	9.24	9.64	10.45	9.28	9.69	9.98	11.11
80	—	—	—	—	—	—	—	—	9.28	9.68	9.93	10.90
Bottom	8.74	8.78	9.84	10.65	9.14	9.25	9.63	10.11	9.28	9.68	9.92	10.56

4. Variation of Temperature and Salinity with Depth in the Southern Entrance

Fig. 5 shows the mean distribution of temperature and salinity with depth at MUIRCHU, Station C, for the months of February, May, August and November. This station is fairly typical of those in the Southern Entrance. The mean depth of the thermocline in August appears to be about 30 m. at all stations, and the maximum salinity gradient occurs at approximately the same depth as the maximum temperature gradient.

The actual depth and sharpness of the thermocline at a given time depend, largely, on the meteorological conditions. In calm, sunny weather it tends to be shallower than usual, while the more thorough mixing due to a period of strong winds causes the thermocline to occur at a greater depth. Fig. 6

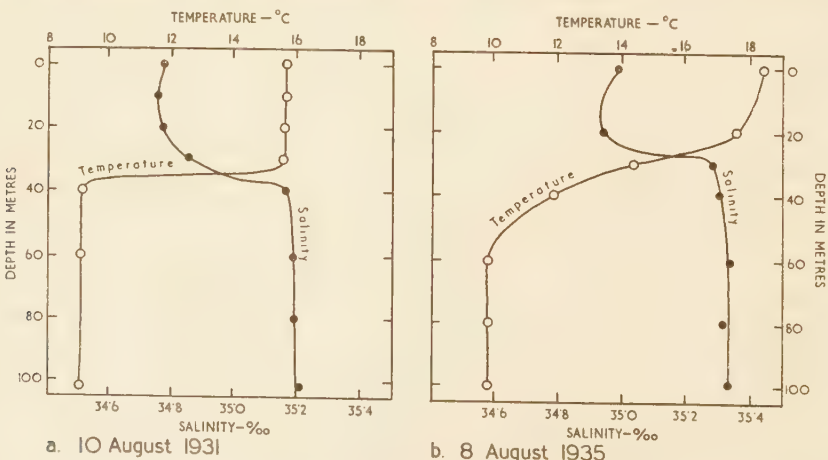
gives temperature and salinity profiles for Station C for two particular days, 10th August 1931 and 8th August 1935, showing the range of conditions that may be expected at a given time of year. In August 1931, the surface temperature was nearly 3°C. lower than in 1935,



5. MUIRCHU, Station C (51° 00' N, 8° 00' W)

Mean vertical distribution of temperature and salinity

gives temperature and salinity profiles for Station C for two particular days, 10th August 1931 and 8th August 1935, showing the range of conditions that may be expected at a given time of year. In August 1931, the surface temperature was nearly 3°C. lower than in 1935,



a. 10 August 1931

b. 8 August 1935

6. MUIRCHU, Station C

Vertical distribution of temperature and salinity in August in two different years

but the constant temperature layer extended deeper and the transition at the thermocline was sharper.

The transition from uniform temperature and salinity conditions from surface to bottom to the development of a thermocline would seem to take place in a comparatively short distance south of a line from Carnsore Point–St. Davids Head. Matthews's (1913) Section V, just north of this line, shows a temperature difference of about 2°C. between surface and bottom in August, while his Section VI, running south-south-east through Stations 39, 40 and 41, shows differences increasing from 3.7°C. at Station 39 to 7.2°C. at Station 41 for the same month. Le Danois (1926) gives a section running from north to south through the Irish Sea, just east of the meridian 6°W, based on observations taken from the s.s. TANCHE in August 1926. This shows the transition as occurring between latitude 52°N and 51° 30'N.

The actual temperature or salinity for a particular month in a particular year will usually be different from the long-period mean for that month. Farran (1921–30) has published, over a number of years, charts and sections based on the MUIRCHU observations for particular months. No systematic analysis of the year-to-year variations appears to have been made, however.

5. Seasonal Variation of Temperature

Surface Temperature

The main features of the mean seasonal variation can be seen directly from the charts (pages 10 and 14) and Table 1 (page 21). For each representative station, the grand monthly mean values of surface temperature were plotted against time and a smooth curve drawn through them. From this curve the minimum and maximum temperatures and the approximate dates on which they occurred were read off. These results and the mean annual range are given in Table 3. It is seen that, as a general rule, the annual range of temperature becomes greater and the dates of minima and maxima become earlier as the coasts are approached. For stations in the centre of the channel the range is only about 6.5°C., but it reaches about 12°C. for stations near the coast of north-west England.

TABLE 3

Mean Seasonal Variation of Sea Surface Temperature at Representative Stations

Station	Minimum Temp.	Maximum Temp.	Range of Temp.	Date of Minimum	Date of Maximum
Stranraer–Larne	6.71	13.46	6.75	Mar. 15	Sept. 7
SOLWAY L.V.	4.67	16.00	11.83	Feb. 7	Aug. 3
BAHAMA BANK L.V.	6.08	14.96	8.88	Feb. 16	Aug. 19
Port Erin Bay	6.90	14.12	7.22	Mar. 3	Aug. 23
MORECAMBE BAY L.V.	4.97	16.62	11.65	Feb. 19	Aug. 11
LIVERPOOL BAR L.V.	5.00	17.10	12.10	Feb. 13	Aug. 9
Holyhead	6.92	15.00	8.08	Mar. 6	Aug. 31
Holyhead–Kish	7.69	14.10	6.41	Mar. 17	Sept. 8
Kish	7.23	14.29	7.06	Mar. 9	Aug. 20
Bardsey L.H.	7.46	15.30	7.84	Feb. 26	Sept. 1
Fishguard–Rosslare	7.72	14.60	6.88	Mar. 23	Sept. 7
CONINGBEG L.V., 1904–15	7.68	14.20	6.52	Mar. 7	Aug. 29
CONINGBEG L.V., 1925–47	8.02	14.50	6.48	Mar. 7	Sept. 7
SEVEN STONES L.V.	9.19	15.86	6.67	Mar. 11	Aug. 9

Temperature at Various Depths in the Southern Entrance

The seasonal variation in the Southern Entrance cannot be investigated with much precision, since mean values are available only for the four months, February, May, August and November, as in Table 2 (page 22). Of these months, the maximum temperature near the surface occurs in

August, but near the bottom it occurs in November, when the thermocline has broken down allowing the warm layer of water above it to become mixed with the colder water below. The minimum temperature occurs in February near the surface, and from February to May near the bottom. The seasonal range is about 7°C. near the surface but less than 2°C. near the bottom.

6. Diurnal Variation of Temperature

From the observations at Port Erin Bay and at certain lightvessels, where observations were made in the early morning and at 4 p.m., the excess of afternoon temperature over morning temperature gives an estimate of the diurnal range of surface temperature. Such a variation is to be expected, due to heating by solar radiation during the day and cooling by back radiation and evaporation at night. Table 4 gives some typical mean values of this excess (taken from Proudman, Lewis and Dennis). The difference is greatest in the summer months and tends to be greater in areas where the water is shallow for a considerable distance from the coast.

TABLE 4
Mean Values of Excess of Afternoon over Morning Sea Surface Temperatures (°C.)

Station	Feb.	May	Aug.	Nov.	Year
Port Erin Bay	0.13	0.48	0.37	0.09	0.28
CAERNARVON BAY L.V.	0.14	0.48	0.57	0.17	0.33
LIVERPOOL N.W. L.V.	0.29	0.87	0.72	0.20	0.51
MORECAMBE BAY L.V.	0.36	0.94	0.84	0.25	0.57
BAHAMA BANK L.V.	0.18	0.62	0.76	0.04	0.38
SOLWAY L.V.	0.42	0.81	0.58	0.29	0.56

7. Tidal Variation of Temperature

Where horizontal temperature gradients exist and the tidal streams run in a direction making an angle with the isotherms, the temperature measured at a fixed station may be expected to show a variation with the tidal period, although the temperature of a given element of water may remain constant. The main constituent of such a variation will be semi-diurnal and its amplitude will be expected to vary with a fortnightly period, corresponding to spring and neap tides.

An additional effect may arise where large areas of beach are alternately exposed and covered by the tide. The beach exposed at low water will be heated to a temperature above that of the water in summer, and cooled to a temperature below that of the water in winter. When the tide rises, the water coming into contact with the beach will gain in temperature in summer and lose in temperature in winter. Such changes of temperature, which will be greater near the time of spring tides than near neap tides, will be communicated to water farther offshore by processes of mixing. Thus the coastal waters will themselves undergo changes of temperature of tidal origin, and these changes will cause modifications in the tidal oscillation of temperature observed at a fixed station. In addition, in summer there will be an accumulation of heat in the coastal waters near the time of spring tides, which will be propagated out to sea near the time of neap tides ; and in winter there will be opposite effects. In this way, a fortnightly constituent will be introduced into the tidal variation of temperature.

The existence of the fortnightly oscillation in temperature was demonstrated by Johnstone (1908), who compared curves of surface temperature at MORECAMBE BAY L.V. with the spring and neap variation of tidal range at Liverpool. The effect was investigated further by Daniel (1920), using temperatures taken daily at 4 p.m. at MORECAMBE BAY, BAHAMA BANK and CAERNARVON BAY L.Vs.

By making use of the twice daily observations of temperature and applying the methods of tidal analysis, Proudman (1938a) was able to determine the amplitudes and phase lags of both the semi-diurnal (M_2) and fortnightly (MS_f) constituents for five lightvessels and Port Erin Bay. The M_2 and MS_f constituents are of the same order of magnitude in each case, but the amplitudes of both are greater for the SOLWAY, MORECAMBE BAY, and LIVERPOOL N.W. lightvessels than for

CAERNARVON BAY L.V., BAHAMA BANK L.V. and Port Erin Bay. This result was to be expected, since at the former three stations the tidal streams run approximately perpendicular to the isotherms, while at the latter three the stream-lines and isotherms run approximately parallel to one another. The amplitudes at the former three stations are given in Table 5. No figures can be given for May, June, and July, since at this season the interval between the sunrise and 4 p.m. observations is too near a tidal period for the analysis to be determinate.

TABLE 5
Amplitudes of Tidal Oscillations of Temperature (°C.)

	Jan.	Feb.	Mar.	Apr.	...	Aug.	Sept.	Oct.	Nov.	Dec.
<i>M₂ constituent</i>										
SOLWAY L.V.	0.44	0.22	(0.05)	(0.07)		(0.26)	0.49	0.52	0.65	0.15
MORECAMBE BAY L.V. ..	0.11	0.22	0.18	0.42		(0.31)	0.22	0.18	0.22	0.16
LIVERPOOL N.W. L.V. ..	0.17	0.15	0.23	(0.10)		0.65	(0.09)	0.23	(0.14)	0.14
<i>MSf constituent</i>										
SOLWAY L.V.	0.17	0.30	0.18	(0.06)		(0.26)	0.37	0.73	0.74	0.32
MORECAMBE BAY L.V. ..	0.07	0.12	(0.08)	0.34		(0.39)	(0.05)	0.21	0.39	0.18
LIVERPOOL N.W. L.V. ..	(0.04)	(0.06)	0.26	(0.15)		0.76	0.22	0.27	0.22	0.13

NOTE—The amplitudes in brackets are rather uncertain, since they are less than their standard deviations

The results for the phase lags (not reproduced here) showed that in the winter months, the maximum temperature in the M_2 oscillation occurs near high water or within 4 hours after it, whereas in August it occurs near low water or within 4 hours after it. For the MSf oscillation, the time of maximum temperature occurs 3 or 4 days after spring tides in August for SOLWAY L.V. and MORECAMBE BAY L.V., and in September for the other stations. In October and November, the maximum occurs from 10 to 14 days after spring tides (i.e., from 3 to 7 days after neap tides) for all stations. These phase relationships are as anticipated for coastal waters from the general explanation given earlier.

8. Irregular Variations of Temperature: correlations

Monthly Anomalies and their Standard Deviations

The mean temperature for a particular month is different, in general, from the corresponding grand monthly mean. The excess of the particular monthly mean value over the grand monthly mean value has been termed the "monthly anomaly" for that particular month. The standard deviation of such anomalies over a number of years is an indication of the variability of the monthly mean temperature at a given station. If a particular monthly anomaly is denoted by x , the standard deviation σ is given by $\sigma = \sqrt{\frac{\sum x^2}{N-1}}$ where the summation is carried out over the total number N

of monthly anomalies considered. The standard deviations of the monthly anomalies for certain representative stations, computed for the months grouped into four quarters and for the whole year, are given in Table 6. The standard deviation, like the mean annual range, tends to be higher for stations near the coast than in the centre of the channel. It also tends to be greater in the winter months than in the summer for all stations, with the exception of Seven Stones.

TABLE 6

Standard Deviations of Monthly Anomalies of Surface Temperature (°C.)

Station	Jan./Feb./Mar.	April/May/June	July/Aug./Sept.	Oct./Nov./Dec.	Year
Stranraer-Larne ..	0.82	0.65	0.47	0.61	0.62
Port Erin Bay	0.66	0.48	0.48	0.58	0.55
MORECAMBE BAY L.V. ..	1.25	0.82	0.49	0.65	0.82
LIVERPOOL BAR L.V. ..	1.33	0.89	0.60	0.71	0.88
Holyhead	0.66	0.54	0.31	0.52	0.50
Holyhead-Kish	0.51	0.44	0.42	0.49	0.45
Kish	0.79	0.49	0.51	0.65	0.60
Bardsey L.H.	0.79	0.52	0.57	0.70	0.63
SEVEN STONES L.V. ..	0.61	0.65	0.87	0.58	0.68
CONINGBEG L.V. ..	0.50	0.44	0.53	0.59	0.51

Extreme Values

As a further indication of the variation which may occur in monthly mean temperatures, Table 7 gives the extreme values of the monthly means at Port Erin Bay, occurring within the 49-year period, 1903-51. For most months the extreme values deviate from the mean by approximately twice the standard deviation.

TABLE 7

Extremes of Monthly and Annual Means of Surface Temperature at Port Erin Bay (1903-51)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	
Mean temperature	8.07	7.15	7.00	7.82	9.25	11.38	13.17	14.05	13.73	12.56	10.86	9.40	10.37	
Standard deviation	0.70	0.65	0.62	0.56	0.44	0.43	0.50	0.43	0.49	0.51	0.60	0.61	0.37	
Extreme Tempera- tures	{ Max. Year	9.3 1932	8.4 1935	8.4 1950	8.9 1943	10.4 1943	12.5 1943	14.3 1905	15.0 1911, 1933	14.8 1933, 1949	13.7 1949	12.2 1951	10.8 1951	11.08 1949
		{ Min. Year	6.3 1941	5.1 1947	5.3 1947	6.0 1917	7.9 1951	10.4 1951	12.1 1919	13.2 1922	12.8 1912	11.3 1919	9.0 1919	8.0 1917

Correlation between Temperatures at Pairs of Stations

The coefficient of correlation between the monthly mean temperatures at two stations is given by

r = (Σx1x2) / (Nσ1σ2)

where r is the correlation coefficient, x1 and x2 are the simultaneous monthly anomalies at the two stations, and σ1 and σ2 are the standard deviations of the monthly anomalies over the total number N of months for which the summation is carried out.

Table 8 gives the coefficients of correlation between monthly temperatures at Port Erin Bay and various other stations in the Irish Sea. As in the case of the standard deviations, the correlation coefficients are shown for the four quarters separately and for the whole year. The coefficients, on the whole, are quite high, particularly during the winter months. It may be concluded that the anomalies in sea surface temperature are governed, to a large extent, by factors which are common to the whole of the Irish Sea.

Correlation between Sea Surface Temperature and Air Temperature

It is of interest to investigate the correlation between the sea surface temperature at a particular station and the air temperature at a neighbouring meteorological station on land. If, in the above

TABLE 8

Correlation between Monthly Surface Temperatures at Port Erin Bay and other Stations (Coefficients)

Stations	Jan./Feb./Mar.	Apr./May/June	July/Aug./Sept.	Oct./Nov./Dec.	Year	Period
Port Erin and Stranraer-Larne ..	0.82	0.70	0.22	0.28	0.61	1935-46
Chicken Rock L.H. ..	0.97	0.80	0.72	0.73	0.86	1935-46
MORECAMBE BAY L.V. ..	0.75	0.75	0.67	0.79	0.74	1935-46
LIVERPOOL BAR L.V. ..	0.82	0.69	0.80	0.88	0.78	1935-46
Holyhead	0.87	0.85	0.71	0.80	0.82	1935-46
Holyhead-Kish	0.81	0.77	0.67	0.62	0.69	1935-46
Kish	0.84	0.71	0.71	0.70	0.75	1935-46
Bardsey L.H.	0.78	0.73	0.52	0.39	0.63	1935-46
SEVEN STONES L.V. ..	0.51	0.55	0.61	0.60	0.57	1903-31
CONINGBEG L.V. ..	0.65	0.72	0.45	0.53	0.59	1925-47

equation for the correlation coefficient, x_1 and x_2 are the monthly anomalies of sea temperature at the oceanographic station and of air temperature at the meteorological station respectively (both defined in the same way), while σ_1 and σ_2 are the corresponding standard deviations, then r will be the coefficient of correlation between sea and air temperatures for the pair of stations considered. Table 9 gives examples of such coefficients, for the four quarters and the year as a whole. Most of the coefficients are fairly high, particularly for sea temperature stations near the coast. In the case of the three stations on the Holyhead-Kish line, it is interesting to note that the correlation between sea temperature at the halfway station and air temperature at Holyhead is lower than that between sea temperature either near Holyhead or near Kish and air temperature at Holyhead. There is a high correlation between the air temperature at any two stations around the Irish Sea (Proudman, Lewis and Dennis).

The correlation between sea temperature and other meteorological factors is referred to in Section 21 (page 49).

TABLE 9

Correlation between Monthly Anomalies of Sea Temperature and of Air Temperature (Coefficients)

Sea Temperature Station	Air Temperature Station	Period	Jan./Feb./Mar.	Apr./May/June	July/Aug./Sept.	Oct./Nov./Dec.	Year
SOLWAY L.V.	Dumfries ..	1907-18	0.53	0.62	0.71	0.79	0.66
BAHAMA BANK L.V. ..	Douglas ..	1907-15	0.76	0.60	0.83	0.76	0.74
Port Erin Bay	Douglas ..	1907-15	0.77	0.52	0.78	0.73	0.70
MORECAMBE BAY L.V. ..	Southport ..	1907-15	0.62	0.55	0.81	0.66	0.66
LIVERPOOL N.W. L.V. ..	Bidston ..	1907-27	0.64	0.55	0.78	0.74	0.68
LIVERPOOL BAR L.V. ..	Bidston ..	1935-46	0.75	0.63	0.66	0.77	0.72
Holyhead	Holyhead ..	1935-46	0.68	0.55	0.53	0.51	0.59
Holyhead-Kish	Holyhead ..	1935-46	0.62	0.58	0.33	0.19	0.46
Kish	Holyhead ..	1935-46	0.72	0.72	0.41	0.53	0.64
CAERNARVON BAY L.V.	Holyhead ..	1907-26	0.62	0.48	0.57	0.62	0.57
CONINGBEG L.V. ..	Waterford ..	1904-15	0.57	0.48	0.60	0.63	0.57

9. Variations in Annual Temperature

The correlation between annual mean temperatures at various stations in the Irish Sea appears to be even higher than the correlation between monthly means. The variation of annual mean temperatures at Port Erin Bay, tabulated in Table 10 for the period 1903-51, may be taken as representative of the Irish Sea as a whole. The annual means for Seven Stones, in the extreme south of the region under investigation, for the periods 1903-38 and 1947-51 are also given. The coefficient of correlation between anomalies of annual temperatures at Port Erin Bay and Seven Stones for the periods 1903-38 and 1947-51 is 0.74, which must be considered high, in view of the

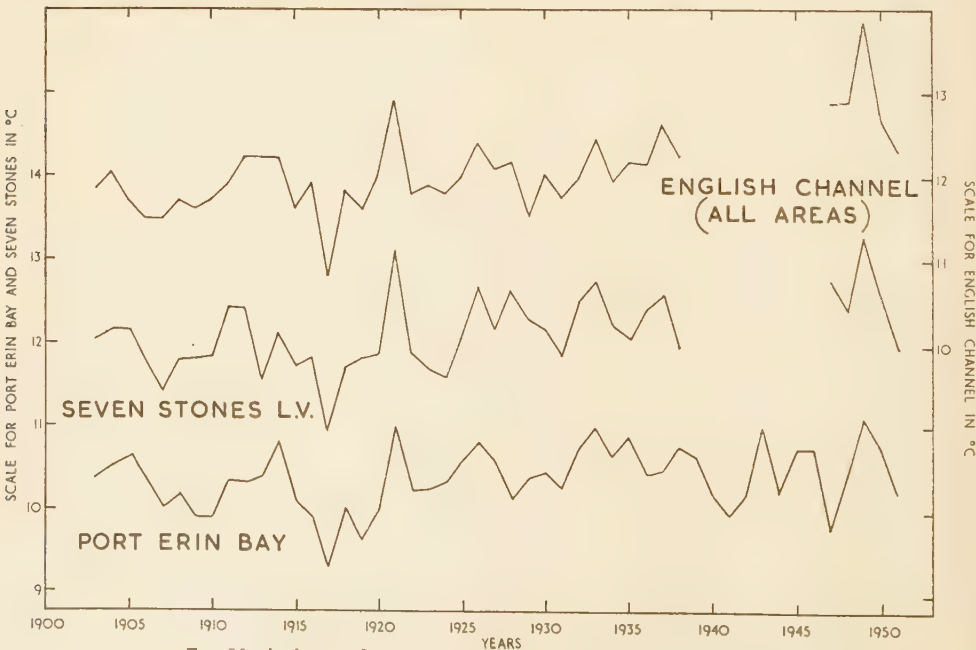
distance separating these two stations. Such correlations are not given for other stations as the series of observations (usually not exceeding 12 years) are comparatively short for this purpose.

TABLE 10
Variations of Annual Mean Temperature (°C.)

Year	Temperature		Year	Temperature	
	Port Erin Bay	Seven Stones		Port Erin Bay	Seven Stones
1903	10.36	12.03	1928	10.13	12.61
1904	10.52	12.17	1929	10.38	12.29
1905	10.62	12.12	1930	10.46	12.17
1906	10.37	11.77	1931	10.26	11.87
1907	10.01	11.41	1932	10.73	12.51
1908	10.17	11.78	1933	10.98	12.75
1909	9.92	11.80	1934	10.65	12.22
1910	9.90	11.83	1935	10.89	12.08
1911	10.32	12.46	1936	10.42	12.41
1912	10.30	12.40	1937	10.48	12.60
1913	10.39	11.56	1938	10.73	11.98
1914	10.78	12.10	1939	10.63	—
1915	10.08	11.71	1940	10.18	—
1916	9.90	11.82	1941	9.94	—
1917	9.31	10.93	1942	10.17	—
1918	10.00	11.70	1943	10.96	—
1919	9.65	11.80	1944	10.22	—
1920	9.98	11.87	1945	10.71	—
1921	10.97	13.10	1946	10.73	—
1922	10.21	11.87	1947	9.80	12.76
1923	10.23	11.69	1948	10.42	12.42
1924	10.31	11.59	1949	11.08	13.29
1925	10.57	12.07	1950	10.75	12.59
1926	10.80	12.68	1951	10.21	11.98
1927	10.56	12.17			

Grand mean values : Port Erin Bay (1903–51) 10.37°C.
Seven Stones (1903–38, 1947–51) 12.12°C.

The annual mean temperatures at Port Erin Bay (1903–51) and Seven Stones (1903–38, 1947–51), as well as the average values for all areas of the English Channel (1903–38, 1947–51), are plotted in Fig. 7. The three curves show a fairly close correspondence. Thus the abnormally low temperature in 1917 and the abnormally high temperature in 1921 appear in all three. The general trend of sea temperature in the Irish Sea and English Channel appears to have been downward from 1903 to 1917 and then upwards until about 1933, after which, in the Irish Sea at least, it tended to fall until 1941, and then to rise again.



7. Variations of annual mean temperature, 1903 to 1951

III. SALINITY

10. Observations

All the determinations of salinity on which this account is based were obtained by the Mohr method, in which the sample of sea water is titrated against silver nitrate solution, with potassium chromate as indicator, using Normal sea water as a standard. The necessary calculations are made using Knudsen's "Hydrographical Tables" (1901). The term "salinity" has a precise definition (see Jacobsen and Knudsen, 1940), but it may be described roughly as the number of grams of salt in 1 kg. of sea water.

In many cases, samples of water for salinity determination were taken at the same time as temperature observations were made. The positions of stations at which regular observations were made are shown in Fig. 2. (page 7).

(A) *Samples from Various Depths*

On all the cruises organized by the Irish Fisheries Branch, the Lancashire and Western Sea Fisheries Committee, and the Marine Biological Association, referred to in Section 1(A) (page 5), samples for salinity determination were taken from the water-bottle at the same time as the temperature was measured.

In his 1913 paper, Matthews published an account of salinity observations at all depths and showed that the vertical distribution of salinity resembles that of temperature. In the winter months the salinity is practically uniform from surface to bottom over the whole Irish Sea. This is also true in the summer months, north of St. George's Channel, but in the Southern Entrance layering of salinity accompanies the temperature layering, with the lower salinity above the thermocline.

(B) *Samples from the Surface Only*

Between 1905 and 1910 the Marine Biological Association arranged for the collection of samples once a week at the BAHAMA BANK and CARDIGAN BAY lightvessels. Surface samples at similar intervals were also obtained from the CONINGBEG L.V. (1909-15), the SOUTH ARKLOW L.V. (1905-06) and the SKULMARTIN L.V. (1905-06), organized by the Irish Fisheries Branch.

On the series of observations on the Holyhead-Dublin route (1922-25, 1926-31), and the Fishguard-Rosslare route (1922-25), referred to in Section 1(B) (page 8), surface samples were collected.

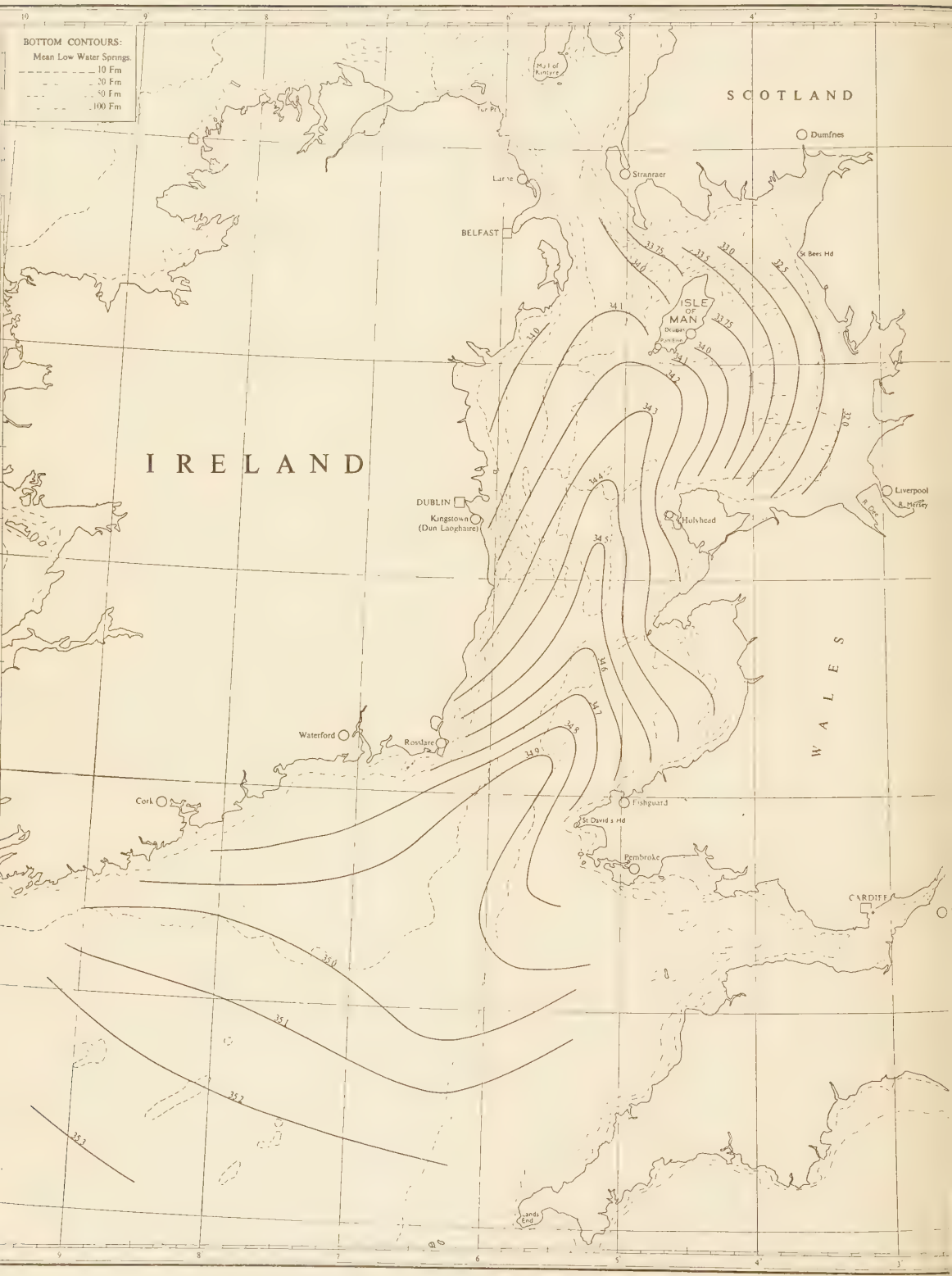
Since 1934 the Oceanography Department of the University of Liverpool has determined the salinity of surface samples taken three times weekly from nine stations.

The remainder of the temperature observations described in Section 1(B) were not accompanied by salinity determinations.

Proudman (1940) published an account of *The Salinity of the Surface Waters of the Irish Sea*, covering all surface observations in the Irish Sea, excluding the Southern Entrance, up to 1939. Observations up to the end of 1946 were included in the analysis by Gilles (1949). For the Southern Entrance the main sources of information are Matthews's paper (1913) and the later work by S.S. MUIRCHU.

11. Charts of Mean Values

Figs. 8(a)-8(e) (pages 30-34) show the mean positions of the surface isohalines for the year as a whole and for the months of February, May, August, and November. Figs. 9(a)-9(e) (pages 35-39) show the bottom isohalines for the Southern Entrance only. These charts are based on grand mean values of salinity, computed for each station in a similar way to the grand mean values of temperature. It has not been thought practicable, however, to reduce the mean values to a common period, as was done in the case of temperature. The following notes refer to the main features shown by the charts.



8 (a). Irish Sea: surface salinity—Year

Ordnance



Ordnance Survey

8 (b). Irish Sea : surface salinity—February



8 (c). Irish Sea : surface salinity—May



8 (d). Irish Sea : surface salinity—August

Ordnance Survey



8 (e). Irish Sea : surface salinity—November

Ordnance Sur





9 (b). Irish Sea : bottom salinity in the Southern Entrance—February

Ordnance Sur



Ordnance Survey

9 (c). Irish Sea : bottom salinity in the Southern Entrance—May



9 (d). Irish Sea : bottom salinity in the Southern Entrance—August

Ordnance Sur



Surface Salinity

The mean annual salinity decreases from 35.3‰ in the extreme south of the Southern Entrance to about 34.0‰ in the North Channel. The isohalines for 34.9‰ and lesser values are markedly convex towards the north, showing the decrease of salinity from the centre of the channel towards the coasts. On the Irish side the minimum salinity obtained is little less than 34.0‰, but off the coast of north-west England the salinity decreases to less than 32.5‰ and is less than 32.0‰ in Liverpool Bay.

The seasonal variations of salinity are not as great as those of temperature, so that the differences between the charts for the separate months and the mean annual conditions are less marked.

The February chart shows the same general features as the annual one, with the salinity in the main channel decreasing from 35.3‰ in the extreme south-west to 34.8‰ at the entrance to St. George's Channel, 34.5‰ in the Holyhead-Dublin channel and 34.0‰ in the North Channel.

In May there is little change.

In August there is a general decrease in surface salinity in the Southern Entrance, especially off the south-east coast of Ireland, where it is now less than 34.7‰. An area of maximum salinity, greater than 34.9‰, appears in St. George's Channel, probably associated with the transition from conditions of salinity layering in the Southern Entrance to vertical uniformity further north. There is a decrease of the order of 0.1‰ in the salinity of the central part of the Irish Sea, but an increase of the order of 0.5‰ in the shallow waters off the coast of north-west England.

In November there is a reversion to winter conditions in the Southern Entrance, but the values are still lower than in February. The area of maximum in St. George's Channel has disappeared and has been replaced by a uniform decrease of salinity northwards. Across St. George's Channel the value of 35.0‰ is higher than in February, but in the Holyhead-Dublin channel the salinity is slightly lower. Off the coast of north-west England, there has been a decrease of salinity since August.

Bottom Salinity between the Isle of Man and Ireland

In the area referred to in Section 2, dealing with temperature, Matthews also found appreciable differences to occur between the salinity at the surface and at the bottom. In a section from Skulmartin to Mull of Galloway, the salinity is lower at the surface than at the bottom by about 0.3‰ in February, and 0.2‰ in May, while in August and November there is little difference. In a section in latitude 54° 00'N from the entrance to Carlingford Lough to just south of the Calf of Man, the corresponding differences are about 0.15‰ or less in February, 0.2‰ in May, 0.15‰ in August, and negligible in November. Rather smaller differences occur in a section in 53° 40'N.

Bottom Salinity in the Southern Entrance

The distribution of mean annual salinity at the bottom resembles that at the surface, but in the Southern Entrance the bottom salinity is somewhat higher than at the surface. The greatest difference, about 0.2‰, occurs off the south-west coast of Ireland.

In February there is little difference between the surface and bottom salinities.

The May charts show little change. Off the south coast of Ireland the surface salinity is rather lower while the bottom salinity is about the same.

In August the surface salinity everywhere in the Southern Entrance is lower than in May. The bottom salinity, in general, has increased slightly, so that it is now considerably higher than the surface salinity. Differences of 0.2‰ to 0.4‰ are common.

In November the surface and bottom isohalines coincide on the east side (off the Bristol Channel) but diverge on the west, the bottom salinity being higher by about 0.1‰.

TABLE II
Grand Mean Values of Surface Salinity at Selected Stations, in ‰

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Period
Stranraer-Larne ..	33.96	33.88	33.98	34.03	34.08	34.04	33.97	33.97	33.97	34.02	33.99	33.98	33.98	1935-1946
BAHAMA BANK L.V. ..	33.57	33.43	33.36	33.38	33.52	33.60	33.61	33.70	33.71	33.79	33.81	33.71	33.59	1905-1910
Chicken Rock L.H. ..	34.10	34.17	34.20	34.24	34.22	34.20	34.15	34.12	34.09	34.03	34.08	34.08	34.14	1935-1946
MORECAMBE BAY L.V. ..	32.31	32.14	32.14	32.33	32.76	32.81	32.83	32.87	32.81	32.71	32.55	32.18	32.54	1935-1946
LIVERPOOL BAR L.V. ..	31.92	31.65	31.44	31.45	31.83	32.09	32.11	32.19	32.19	32.25	31.94	31.66	31.89	1935-1946
Holyhead ..	34.04	34.18	34.10	34.15	34.13	34.19	34.24	34.23	34.21	34.17	34.06	34.05	34.15	1935-1946
Holyhead-Kish ..	34.55	34.58	34.55	34.51	34.46	34.42	34.36	34.34	34.32	34.36	34.41	34.52	34.45	1935-1946
Kish ..	34.22	34.20	34.12	34.15	34.13	34.20	34.17	34.12	34.10	34.12	34.22	34.28	34.17	1934-1946
Bardsey L.H. ..	34.26	34.26	34.28	34.29	34.30	34.28	34.31	34.32	34.38	34.36	34.26	34.27	34.29	1935-1946
CARDIGAN BAY L.V. ..	34.54	34.45	34.39	34.42	34.40	34.34	34.38	34.46	34.50	34.67	34.71	34.62	34.49	1905-1909
Fishguard-Rosslare ..	34.95	34.82	34.77	34.67	34.74	34.76	34.94	35.02	35.06	35.06	35.04	34.98	34.89	1934-1941
CONINGBEG L.V. ..	34.67	34.69	34.69	34.70	34.75	34.63	34.67	34.70	34.82	34.86	34.81	34.69	34.72	1909-1915
SEVEN STONES L.V. ..	35.27	35.27	35.26	35.26	35.24	35.23	35.22	35.19	35.19	35.23	35.26	35.26	35.23	1903-1938
	35.21	35.24	35.26	35.24	35.25	35.25	35.23	35.20	35.15	35.20	35.29	35.26	35.23	1947-1951

12. Mean Values at Representative Stations

Corresponding to Table 1 (page 21) for surface temperatures, Table 11 gives grand mean values of surface salinity for each month and for the whole year for thirteen representative stations. Compared with the stations in Table 1, Table 11 omits the SOLWAY L.V., at which observations of temperature only were obtained ; Chicken Rock L.H., which is in a more open position, replaces Port Erin Bay as the station representing the south end of the Isle of Man, and CARDIGAN BAY L.V. is an additional station. The positions of the two new stations and the periods of observation are:

			Latitude, N		Longitude, W		Period of Observation
Chicken Rock L.H.	..	..	54	02	4	50	Jan. 1935–Dec. 1946
CARDIGAN BAY L.V.	..	..	52	24	5	00	Oct. 1905–Aug. 1909

The details for the other stations are as in Section 3 (page 20).

Table 12 gives the mean values of salinity at various depths at the same three representative stations in the Southern Entrance for which the temperatures were given in Table 2 (page 22).

The variation of salinity with depth at Station C, as typical of the Southern Entrance, is shown in Figs. 5 and 6 (page 22), which have already been discussed in Section 4 (page 22) in connection with temperature.

TABLE 12
Mean Values of Salinity at Various Depths at Three Stations in the Southern Entrance
(Observations taken between 1920 and 1936)

Depth (m.)	A. 51° 40'N, 8° 00'W				C. 51° 00'N, 8° 00'W				E. 50° 20'N, 8° 00'W			
	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.
0	34·92	34·82	34·74	34·94	35·23	35·16	34·93	35·10	35·28	35·29	35·15	35·25
20	34·97	34·88	34·78	34·94	35·22	35·15	34·94	35·10	35·27	35·28	35·18	35·20
40	35·01	35·02	34·93	34·98	35·22	35·17	35·21	35·11	35·28	35·29	35·26	35·21
60	35·03	35·04	34·96	35·01	35·21	35·17	35·24	35·15	35·28	35·29	35·31	35·27
80	—	—	—	—	—	—	—	—	35·29	35·30	35·29	35·27
Bottom	35·05	35·06	35·00	35·08	35·21	35·17	35·28	35·23	35·28	35·30	35·32	35·30
Mean	35·00	34·97	34·89	34·99	35·22	35·16	35·15	35·15	35·28	35·29	35·27	35·25

13. Seasonal Variation of Salinity

Surface Salinity

There is an appreciable seasonal variation in the surface salinity at most stations, but the range of variation and the months in which the maximum and minimum occur vary widely from one station to another. The details of the mean seasonal variation for each of the representative stations have been found graphically, as in the case of temperature, and the results are given in Table 13. The dates of maxima and minima are given only to the month, as greater precision is impracticable and, as indicated in the notes at the foot of the table, in some cases even the month is indeterminate.

The greatest ranges are for two stations in shallow water near the coast (Morecambe Bay and Liverpool Bar), for which the minimum occurs in spring and the maximum in late summer or autumn.

TABLE 13
Mean Seasonal Variation of Surface Salinity at Selected Stations

Station	Minimum Salinity	Maximum Salinity	Range of Salinity	Month of Min.	Month of Max.
Stranraer-Larne	33·88	34·08	0·20	Feb.	May
BAHAMA BANK L.V.	33·36	33·81	0·45	Mar.	Nov.
Chicken Rock L.H.	34·05	34·24	0·19	Oct.	Apr.
MORECAMBE BAY L.V.	32·12	32·86	0·74	Feb.-Mar.	Aug.
LIVERPOOL BAR L.V.	31·42	32·25	0·83	Mar.-Apr.	Sept.-Oct.
Holyhead	34·05	34·24	0·19	Dec.-Jan.	July-Aug.
Holyhead-Kish	34·32	34·58	0·26	Sept.	Feb.
Kish ¹	34·10 (34·12)	34·28 (34·20)	0·18	Sept. (Mar.)	Dec. (June)
Bardsey L.H. ²	34·26	34·39	0·13	Nov.-Feb.	Sept.-Oct.
CARDIGAN BAY L.V.	34·35	34·72	0·37	June	Nov.
Fishguard-Rosslare	34·69	35·07	0·38	Apr.	Sept.-Oct.
CONINGBEG L.V.	34·64	34·86	0·22	June	Oct.
SEVEN STONES L.V. ³	35·19	35·27	0·08	Aug.-Sept.	Jan.-Feb.

NOTES : ¹ *Kish* : there are two maxima and two minima, the figures and months for the secondary maximum and minimum being in brackets.

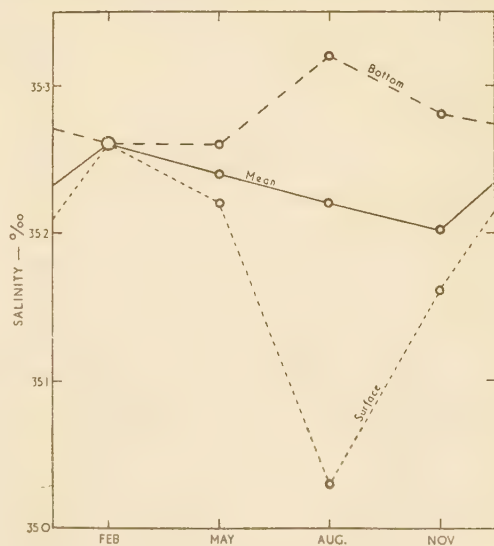
² *Bardsey* : the minimum is very indistinct, the salinity being practically constant from November to February.

³ *Seven Stones* : the seasonal variation is very slight, and the variation in salinity from November to April is little more than 0·01 ‰.

Salinity at Various Depths in the Southern Entrance

The mean seasonal variation of salinity in the Southern Entrance is shown in Fig. 10, in which each point represents a mean value over all the MUIRCHU stations except A (nearest the coast). The surface and bottom values and the mean with respect to depth are shown for each of the four months. In August, the salinity reaches its minimum near the surface, but its maximum near the bottom. The maximum surface salinity is less well defined but appears to occur between February and May, while there is little difference in the bottom salinity between November, February and May. The annual range in salinity is of the order of 0·2‰ at the surface but 0·1‰ or less near the bottom.

The salinity at stations in the entrance to the Bristol Channel shows some unusual features. At the more seaward stations, E26, E29 and E30, the surface salinity is a minimum in August and a maximum in November-February, which is in general agreement with the rest of the Southern Entrance, although the range is of the order of 0·4‰ at E29 and E30. At E27, however, the August minimum does not appear but there is a pronounced minimum in February, which may be due to the winter maximum of run-off from the Bristol Channel. At E28, to the north-west of E27, a comparable decrease in salinity occurs, but later, giving a minimum in May. The range is of the order of 0·4‰. The range in bottom salinity at the first three stations is comparatively small. At



10. Seasonal variation of salinity in the Southern Entrance
(Mean of all MUIRCHU stations, except A)

The range in bottom salinity at the first three stations is comparatively small. At

E27 the bottom salinity is at a minimum in February, although it is 0.22‰ higher than the surface salinity in that month. At E28 the May minimum is as pronounced near the bottom as at the surface. These results are obtained from data on the Marine Biological Association cruises of 1907–09. No data appear to have been published for this area in recent years.

14. Tidal and other Short-period Variations of Salinity

Where horizontal salinity gradients exist and the tidal streams run at an angle to the isohalines the salinity observed at a fixed station may be expected to show a variation with the tidal period, just as in the case of temperature. Using the numerical values of the gradients and tidal currents, salinity variations with amplitudes of the order of 0.4‰ at Liverpool Bar but only 0.03‰ halfway between Holyhead and Dublin may be expected. Bassett (1907) published results for a station near Morecambe Bay showing tidal oscillations with a semi-range of 0.12‰ at the surface, 0.07‰ at a depth of 9 m., and 0.05‰ at the bottom, in a depth of about 40 m.

The existence of tidal variations was investigated more fully by Proudman (1943), using surface observations taken at a fixed hour of the day, three times a week, between May 1934 and December 1939, at seven stations distributed over the Irish Sea. Definite tidal oscillations of salinity were found only for Liverpool Bar and Morecambe Bay. The maximum salinity occurred near the time of high water. More detailed analysis gave the average amplitude throughout the year as 0.294‰ at Liverpool Bar and 0.133‰ at Morecambe Bay. The amplitude varied irregularly from month to month, and no distinct seasonal effect could be established.

Proudman also investigated the daily anomalies at the seven stations, a “daily anomaly” being defined as the excess of the salinity on a particular day over the corresponding monthly mean. The standard deviations of these anomalies are given in Table 14. At Morecambe Bay and Liverpool Bar, where the largest values occur, there is a marked seasonal variation, the anomalies being greater in the winter months. At Holyhead–Kish, typical of the stations with smaller daily anomalies, the seasonal variation is small.

The non-tidal variations for Morecambe Bay and Liverpool Bar can be estimated from the residual daily anomalies, after the tidal variation has been subtracted. The standard deviation of such residual anomalies is 0.381‰ for Morecambe Bay and 0.470‰ at Liverpool Bar. It appears that, even for these two stations, the greater part of the variations observed from day to day are not due to a regular tidal oscillation.

TABLE 14
Standard Deviations of Daily Anomalies of Surface Salinity (‰)

Station	Period	Jan. Feb. Mar.	Apr. May June	July Aug. Sept.	Oct. Nov. Dec.	Year
Chicken Rock L.H. ..	1935–36	—	—	—	—	0.089
MORECAMBE BAY L.V. . .	1934–40	0.510	0.256	0.167	0.505	0.384
LIVERPOOL BAR L.V. ..	1934–40	0.655	0.426	0.333	0.597	0.511
Holyhead–Kish	1934–41	0.129	0.110	0.098	0.121	0.115
Kish	1935–36	—	—	—	—	0.129
Bardsey L.H.	1935–36	—	—	—	—	0.185
Fishguard–Rosslare ..	1935–36	—	—	—	—	0.168

15. Irregular Variations of Monthly Mean Salinities: correlations

Monthly Anomalies and their Standard Deviations

Monthly anomalies of salinity are defined in a similar way to monthly anomalies of temperature, i.e., the monthly anomaly is the excess of a particular monthly mean value over the corresponding grand monthly mean. The standard deviations of such anomalies for certain representative stations are given in Table 15. The standard deviations are highest for Morecambe Bay and Liverpool Bar, the stations which have also the greatest seasonal variation of salinity and the largest daily anomalies. There is a tendency for the standard deviations to be lower in the summer months, but this effect is not so pronounced as in the case of temperature.

TABLE 15

Standard Deviations of Monthly Anomalies of Surface Salinity (‰) (Period 1935-46)

Station	Jan./Feb./Mar.	Apr./May/June	July/Aug./Sept.	Oct./Nov./Dec.	Year
Stranraer-Larne	0.32	0.32	0.26	0.30	0.29
Chicken Rock L.H. ..	0.21	0.22	0.17	0.15	0.18
MORECAMBE BAY L.V. ..	0.45	0.39	0.43	0.47	0.42
LIVERPOOL BAR L.V. ..	0.55	0.55	0.46	0.60	0.50
Holyhead	0.30	0.30	0.22	0.16	0.24
Holyhead-Kish	0.25	0.20	0.14	0.16	0.19
Kish	0.19	0.15	0.18	0.13	0.16
Bardsey L.H.	0.24	0.24	0.18	0.19	0.21

Persistence of Monthly Anomalies

The degree of persistence of the monthly anomalies at a given station may be judged by the rate at which the auto-correlation coefficients fall off with increasing intervals of time. If x_n is the monthly anomaly for the n th month at a given station and x_{n-k} is the anomaly at the same station for month $n+k$, then the auto-correlation coefficient r_k for an interval of k months is given, with sufficient precision, by

$$r_k = \frac{\sum_{n=1}^{N-k} x_n x_{n+k}}{(N-k)\sigma^2}$$

where σ is the standard deviation of the anomalies.

Table 16 gives the auto-correlation coefficients for intervals up to 6 months for six stations. It is seen that, initially, the auto-correlation falls off more rapidly for Morecambe Bay, Liverpool Bar, and Stranraer-Larne than for the other stations, but after 6 months this distinction no longer holds. The values of these coefficients are of interest to compare with those in Table 17 (page 46) described below.

TABLE 16

Persistence of Monthly Anomalies of Surface Salinity (Auto-correlation Coefficients)

Station	Interval (Months)				
	0	1	2	4	6
Stranraer-Larne ..	1.00	0.59	0.48	0.41	0.31
Chicken Rock L.H.	1.00	0.83	0.68	0.52	0.41
MORECAMBE BAY L.V.	1.00	0.59	0.41	0.44	0.40
LIVERPOOL BAR L.V.	1.00	0.52	0.42	0.37	0.29
Holyhead-Kish ..	1.00	0.72	0.58	0.37	0.29
Fishguard-Rosslare	1.00	0.67	0.52	0.38	0.26

Correlation between Salinities at Pairs of Stations

Table 17 gives, for various pairs of stations, the coefficient of correlation between the monthly anomaly at one station and the monthly anomaly at a second station, either for the same month or for a stated number of months later. For some pairs of stations, the correlation coefficient reaches a maximum for a time lag of several months, e.g., Holyhead-Kish and Chicken Rock (2 months), Holyhead and Liverpool Bar (4 months). The correlation between Fishguard-Rosslare and Holyhead-Kish reaches a maximum after 12 months (not shown in the Table), when the correlation coefficient is 0.42.

The possible interpretation of these time lags in terms of water movements is referred to in Section 36 (page 56), dealing with currents.

TABLE 17

Correlation between Monthly Anomalies of Surface Salinity at Various Pairs of Stations (Coefficients)

Station (1)	Station (2)	Months by which Station (2) is later than Station (1)					
		-2	0	2	4	6	8
Fishguard-Rosslare	Holyhead-Kish ..	0.20	0.35	0.25	0.31	0.22	0.21
Holyhead-Kish ..	Chicken Rock L.H.	0.45	0.69	0.71	0.47	0.44	—
Holyhead-Kish ..	Stranraer-Larne	—	0.31	—	—	—	—
Holyhead-Kish ..	Kish	—	0.45	—	—	—	—
Holyhead-Kish ..	Holyhead ..	—	0.72	—	—	—	—
Holyhead	LIVERPOOL BAR L.V.	—	0.38	0.41	0.43	0.39	—
LIVERPOOL BAR L.V.	MORECAMBE BAY L.V.	0.40	0.56	0.45	—	—	—
Chicken Rock L.H.	Stranraer-Larne	0.35	0.59	0.50	0.41	0.43	0.36

16. Variations in Annual Salinity

From the eight stations (Table 11, page 41) for which observations from 1935 to 1946 are available, there appears to be a fairly close correlation between annual means of salinity at the various stations, with the exception of Stranraer-Larne. From 1936 to 1938 the annual salinity fell at most stations, while the years 1940-42 had mean salinities above the average. Another decrease followed.

TABLE 18

Variations of Mean Annual Surface Salinities on the Holyhead-Dublin Line

<i>Year</i>	<i>Salinity</i>	<i>Stations used</i>	<i>Year</i>	<i>Salinity</i>	<i>Stations used</i>	
1909	‰ 34·20	Irish cruises 16, 17, 18, 19.	1934	‰ 34·47	Nr. Holyhead Holyhead-Kish Near Kish	
1910	34·17		1935	34·40		
1911	34·28		1936	34·43		
1912	34·52		1937	34·22		
1913	34·53		1938	34·12		
1914	34·47		1939	34·13		
			1940	34·38		
1922	34·12	Holyhead-Dublin I, II, III, IV. (two series)	1941	34·33		
1923	34·26		1942	34·36		
1924	34·35		1943	34·30		
1925	34·38		1944	34·16		
1926	34·39		1945	33·97		
1927	34·36		1946	34·28		
1928	34·50		1947	34·28		
1929	34·52		1948	34·14		
1930	34·44		1949	34·19		
1931	34·19		1950	34·39		
			1951	34·43		

Grand mean value 34.31‰

and 1945 was a year of unusually low salinity at all stations. The individual yearly means are not given, but Table 18 gives the mean annual salinity on the Holyhead-Dublin line for a number of years between 1909 and 1951. The stations used in computing the mean values are indicated in the Table. The values given may be taken as typical of the year-to-year variation of salinity in the central part of the Irish Sea. A comparison of the annual means for the English Channel for 1903 to 1927 (Lumby, 1935) with the Holyhead-Dublin ones, as far as they overlap, does not show any clear correspondence such as was apparent for the annual temperatures.

IV. PHYSICAL PROCESSES AFFECTING TEMPERATURE

17. General Principles

The distribution of temperature in the sea is determined, in general, by the effects of radiation and exchange of heat with the atmosphere, and by currents and turbulent mixing in the sea. The influence of the proximity of land is to cause a larger annual range of surface temperature near the coasts than in the open sea. This was pointed out by Dickson (1899), who found that for a number of coastal stations round the British Isles the mean excess of sea temperature over air temperature never exceeded 2°C . and was frequently much less. Dickson also referred to the greater horizontal mixing, and hence more uniform distribution of temperature in areas where the tidal streams were strong. The thorough vertical mixing, which results in a nearly uniform temperature from surface to bottom over a large part of the Irish Sea, is also due mainly to the effect of tidal streams (Johnstone, 1908 ; Matthews, 1913).

18. Energy Balance Equation

In discussing quantitatively the processes affecting temperature, the energy balance in any region of sea may be represented by the equation

$$Q_s = Q_B + Q_E + Q_C + Q_\theta + Q_v$$

where

Q_s is the heat absorbed from incoming solar radiation,

Q_B is the effective back radiation from the sea to the atmosphere and space,

Q_E is the heat energy lost by evaporation to the atmosphere,

Q_C is the heat lost by conduction to the atmosphere,

Q_θ is the heat used in raising the temperature of the water within the region, and

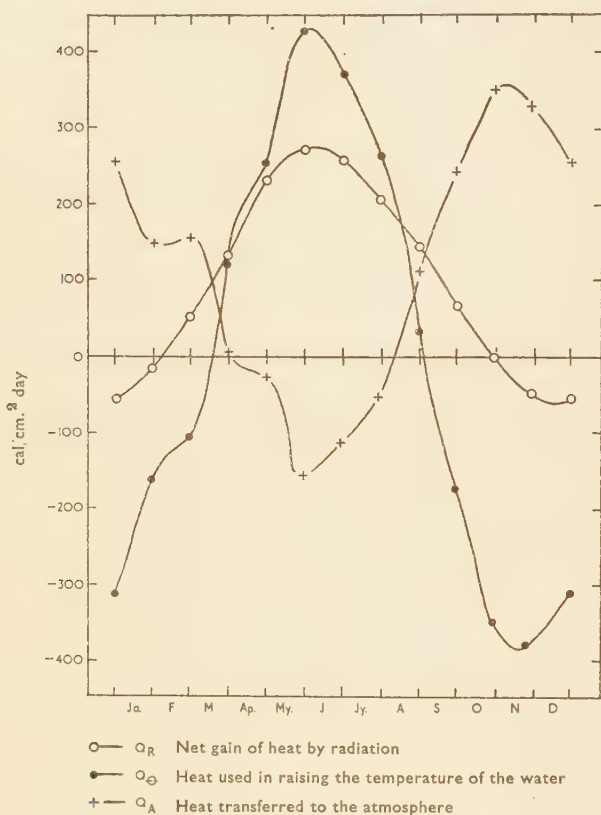
Q_v is the heat transferred to adjacent regions of sea by currents and by horizontal mixing.

In coastal waters it may be necessary to add a term Q_L to the right-hand side of the equation, representing heat transferred to the land. This may occur, for example, in the north-eastern part of the Irish Sea, where large areas of sandbanks off the Lancashire coast are alternately covered and exposed by the tide. In summer, the temperature of exposed areas may rise considerably above that of the off-shore water, so that with the incoming tide quantities of heat are transferred to the water, to be carried away from the coasts when the tide recedes. The reverse process may occur in winter. In deeper water Q_L may safely be neglected.

19. Seasonal Variation in Dublin-Holyhead Channel

The above equation has been applied to the mean seasonal variation of temperature in the channel between Dublin and Holyhead (Bowden, 1948). Here the isotherms run nearly north and south at all seasons, and the drift of water is slow, so that there is unlikely to be much transport along the channel either by advection or mixing. The effect of mixing across the channel may be eliminated by considering mean conditions in a section across it from coast to coast. Thus $Q_v = 0$. Actual measurements of radiation have not been made for the Irish Sea, but estimates may be made of Q_s and Q_B for each month of the year with a fair degree of confidence from tables, using observed values of sea surface temperature, relative humidity and cloudiness. Writing $Q_R = Q_s - Q_B$ gives the "radiation surplus," i.e., the net gain of heat energy by radiation for each month in calories per cm^2 of surface, as shown in Fig. 11 (page 48). It is seen that Q_R is positive throughout the year except for the three months, November, December, and January.

From the monthly means of sea surface temperature at stations on the Holyhead-Dublin line, assuming the temperature to be uniform from surface to bottom, Q_0 , the heat used in raising the temperature of a column of water of 1 cm.² cross-section each month may be computed. Values



11. Seasonal variation of heat processes in the Holyhead-Dublin channel

unlikely, however, that there will be a net gain of heat from the atmosphere, as shown by the curve of Q_A from April to August. It is possible that Q_0 may have been over-estimated, due to the presence of slight vertical temperature gradients in summer which have been neglected.

20. Transfer of Heat by Horizontal Mixing

It may be concluded that the seasonal variation of the heat content of the Holyhead-Dublin section as a whole is governed mainly by the local effects of radiation and exchange of heat with the atmosphere. Instead of considering the section as a whole, however, one may imagine the channel divided into three narrower, parallel channels, two fairly shallow ones near the coasts and a deeper one in the centre, and compute the increments Q_0 for each separately. If this is done, it is found that the central channel shows a greater gain of heat than the two coastal channels in summer and a greater loss in winter. This is consistent with the idea that there is a transfer of heat from the coastal areas towards the centre of the section in summer, and in the reverse direction in winter. Qualitatively, the process may be described as follows, on the assumption that the water in a vertical column from surface to bottom is completely mixed. In summer, since the net gain of heat by radiation is not likely to vary much across the section, the increase in heat content of a vertical column will tend to be the same, whether it is near the coasts or in the centre of the channel. In the coastal water, however, the heat being distributed through a shorter column of water will cause a greater rise in temperature. In this way horizontal gradients of temperature will arise, and the processes of horizontal mixing will cause heat to be transferred from the sides of the channel towards the centre.

Other parts of the Irish Sea do not lend themselves so readily to a direct application of the energy equation, but from the similarity in the seasonal variation of temperature there seems to be little doubt that the same processes are taking place.

of Q_0 are shown in Fig. 11, which also shows the difference $Q_A = Q_R - Q_0$. From the first equation, it follows that $Q_A = Q_E + Q_0$ and represents the total heat energy transferred to the atmosphere. The figure shows Q_A to be a maximum in autumn and early winter, which is in agreement with results for other regions in temperate latitudes.

To separate the effects of conduction and evaporation, a knowledge of the ratio $R = Q_c/Q_E$ is required. R , usually known as the "Bowen ratio", is given by

$$R = 0.66 (\theta_w - \theta_a)/(e_w - e_a)$$

where θ_w and θ_a are the temperatures at the sea surface and in the air at a standard height above the surface, in °C., and similarly e_w and e_a are the vapour pressures at the same positions in mb. Using the data for Holyhead, it is found that R is positive from September to March, reaching a maximum of 0.53 in December-January, and negative from April to August, reaching a minimum of -0.77 in June-July. The mean value for the whole year is 0.12. The negative values in summer mean that the sea is gaining heat by conduction from the air above it while losing heat by evaporation. It seems

21. Irregular Variations of Temperature : correlation with Meteorological Factors

In addition to the mean seasonal variation, the sea temperature shows irregular variations from month to month and from year to year. The deviation of the mean temperature for any particular month from the long-period mean for that month has been termed the "monthly temperature anomaly". If the processes of radiation and exchange of heat with the atmosphere are mainly responsible for the mean conditions, one might expect to be able to trace temperature anomalies to corresponding anomalies in these processes. It has not yet been found possible to do this by the energy equation method. A different approach can be made, however, by considering the correlation coefficient between anomalies in sea temperature and anomalies in one or other of the meteorological factors (Proudman, Lewis and Dennis, 1937).

The correlation between sea surface temperature and air temperature has already been discussed in Section 8 (page 25).

A significant correlation was found also between sea temperature and barometric gradient (i.e., mean wind), for a number of stations. For example, in the first and last quarter of the year, a south wind appears to have the effect of raising the sea temperature of stations towards the east side of the sea. The isotherms run nearly north and south at these seasons, with the temperature increasing to westward. A south wind may be expected to cause a transport of water towards the east, thus bringing water of higher temperature towards the stations in question.

The correlations between sea temperature and sunshine duration, and between sea temperature and cloud amount were also examined, but in most cases the coefficients were rather small. Since the effect of sunshine is to cause heating of the sea by the absorption of solar radiation and the effect of cloud is to reduce cooling by back radiation, either sunshine or cloud, acting independently, would be expected to have a positive correlation with the sea temperature. In fact, anomalies of sunshine duration and of cloud amount for the same month are usually of opposite sign, so that the effects tend to cancel. In summer, however, the effect of sunshine predominates, giving a residual correlation which is positive for sunshine and negative for cloud amount. In winter, the effect of back radiation predominates and the signs of the correlation coefficients are reversed.

22. Temperature Layering in the Southern Entrance

In the Southern Entrance and a few exceptional areas in other parts of the Irish Sea, vertical mixing is not strong enough in the summer months to ensure that the heat content of a vertical column is uniformly distributed. Since heating by absorption of solar radiation is taking place near the surface, the density of the surface water is reduced compared with that of the water below. A stable stratification of the water occurs, therefore, with an upper layer in which the temperature is much increased, while heat is conducted to the lower layer only very slowly. The transition from one layer to the other (the thermocline) is often quite sharp.

In autumn, when there is a net loss of heat from the surface, the water near the surface is cooled, becomes denser, and convection currents are set up. These extend to an increasing depth until the whole vertical column of water is completely mixed.

The formation of a warm upper layer in summer and its stability when formed have been discussed by Atkins (1925), referring to the western part of the English Channel, where similar conditions occur.

V. PHYSICAL PROCESSES AFFECTING SALINITY

23. Annual Rainfall, Evaporation and Run-off

The salinity of the Irish Sea is determined by the salinity of the incoming Atlantic water as modified by rainfall and evaporation over the sea, run-off from the coasts, and the effects of currents and turbulent mixing. Estimates of rainfall, evaporation and run-off have been made recently to provide data for an application of Knudsen's method for estimating the mean flow (see Chapter VI, page 53). The annual rainfall over the northern part of the Irish Sea has been estimated to be 98 mm. (Glasspoole, 1949), and this is probably a fair estimate for the remaining parts of the Sea as well. No observations of evaporation have been made, but by the energy balance method an

estimate of 574 mm. per year has been made for the Holyhead–Dublin channel. Taking this figure, also, as typical of the whole Irish Sea, there is an annual excess of rainfall over evaporation of 224 mm.

Table 19 shows the total volumes of fresh water added per year to the three regions of the Irish Sea, into which it was divided for the purpose of applying Knudsen’s method. The volumes of run-off from the land areas draining to these three regions are similarly shown. The run-off has been estimated from the general rainfall over the catchment areas reduced by the estimated loss, which is due mainly to evaporation.

TABLE 19
Rainfall, Evaporation and Run-off over the Irish Sea and Areas Draining to it

Region	I South		II Central		III North		Whole Sea
	W. side	E. side	W. side	E. side	W. side	E. side	
<i>Land Areas</i>							
Area km. ²	17,250	32,550	3,700	5,130	8,060	26,080	92,770
Rainfall in./yr.	41·9	39·6	42·3	56·2	35·7	47·3	
Loss in./yr.	17	19	17	19	17	17	
Run-off .. { in./yr.	24·9	20·6	25·3	37·2	18·7	30·3	
	mm./yr.						
Volume of fresh water added .. km. ³ /yr.	633	523	643	945	475	770	
	10·91	17·01	2·38	4·84	3·83	20·08	
	27·92		7·22		23·91		59·05
<i>Sea Areas</i>							
Area km. ²	52,420		18,570		28,610		99,600
Rainfall, P in./yr.			31·4				
Evaporation, E in./yr.			22·6				
P-E in./yr.			8·8				
			224				
Volume of fresh water added .. km. ³ /yr.	11·74		4·16		6·41		22·31
Total volume of fresh water added .. km. ³ /yr.	39·66		11·38		30·32		81·36

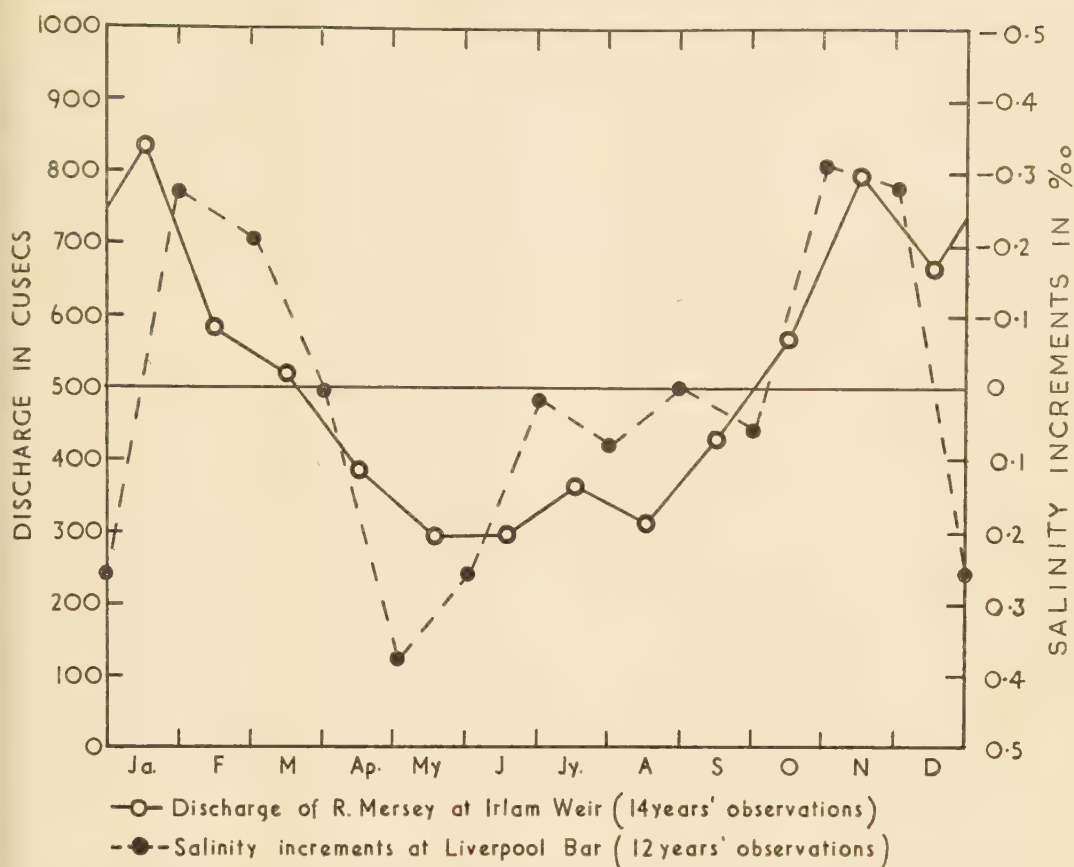
24. Mixing by Horizontal Turbulence

The total effect of the processes of rainfall, evaporation, and run-off on the mean salinity is to cause a gradual decrease from south to north as the water drifts slowly through the Irish Sea. In addition to transport of salt by the current, salt is transported into the Sea from both south and north by turbulent mixing. From data for the Southern Entrance the mean value of K_x , the coefficient of eddy diffusion in the direction of the current, has been estimated to be between 5×10^6 and 9×10^6 cm.²/sec. in this region.

The fresh water which is added at the coasts diffuses gradually towards the centre of the channel, the salinity increasing from the sides towards the centre. From the shape of the isohalines in the central part of the Irish Sea, Proudman (1948) has deduced that $K_y/U = 4 \times 10^5$ cm., where K_y is the coefficient of eddy diffusion transverse to the mean flow and U is the mean current.

25. Seasonal Variations in Coastal Waters

In many parts of the Irish Sea the salinity has a seasonal variation, but the range of the variation and the date of maximum salinity vary greatly from one place to another. Since the mean salinity is determined by the processes of rainfall, evaporation, and run-off, one may look to seasonal variations in these processes for the causes of variations in salinity. Near the coasts the seasonal variation of salinity reflects the variation in run-off. A close correlation is found, for example, between the discharge of the River Mersey and the salinity at Liverpool Bar. Fig. 12 (page 51) shows the mean monthly values of the discharge and the monthly increments of salinity. From the data available, this discharge curve is fairly typical, the minimum in summer being followed by a rapid rise in the autumn to a high value which is maintained throughout the winter. The salinity at coastal stations follows this curve, the maximum salinity lagging a month or two behind the minimum discharge, and occurring in August or September.



12. Seasonal variation of discharge of River Mersey, compared with salinity at Liverpool Bar

26. Seasonal Variations in the Open Sea

The amplitude of the seasonal variation of salinity due to run-off decreases fairly rapidly as one goes away from the coasts. In the open sea, a more important process may be the seasonal variation in the excess of rainfall over evaporation over the sea itself. To get an idea of the possible magnitude of the effect, consider a column of water of unit cross-section and of depth h , which is completely mixed. Suppose that in a given interval of time, say one month, the evaporation is E and precipitation P . Assuming that there is no other change in the freshwater content and no change in the salt content of the column, the salinity will change from S to $S + \Delta S$, where

$$Sh = (S + \Delta S)(h + P - E)$$

Thus $\Delta S = \frac{-(P - E)S}{h}$ approximately.

No observations have been made of the seasonal variations of rainfall or evaporation over the Irish Sea, but estimates made indirectly are shown in Table 20. The variation of rainfall has been estimated from that at surrounding land stations. Estimates of monthly values of E have been made by two different methods (Bowden, 1950): (a) the energy balance equation; (b) the evaporation equation deduced by Sverdrup on hydrodynamical principles. The two estimates are in qualitative agreement but the latter method gives a smaller range. The values of E given in the table are the mean of the two estimates. The table also gives $P - E$ and the corresponding seasonal variation of salinity in a column of water, 100 m. deep, completely mixed. The salinity is given as a maximum in March and a minimum in August–September, with a range of 0.057‰.

This estimate can be compared with the seasonal variation of the mean salinity from surface to bottom in the Southern Entrance (Fig. 10, page 43). There is seen to be fair agreement with observations, both in time of maximum and in seasonal range.

TABLE 20
Estimated Seasonal Variation of Rainfall and Evaporation over the Irish Sea, and the consequent Variation in the Mean Salinity of a Column of Water 100 m. deep

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Rainfall P	 mm.	66	58	58	48	52	54	67	82	61	85	81	86	798
Evaporation E	 mm.	69	53	35	7	5	4	6	30	68	97	106	94	574
P-E	 mm.	-3	5	23	41	47	50	61	52	-7	-12	-25	-8	224
Salinity deviation ‰ from annual mean	0.011	0.019	0.024	0.022	0.014	0.005	-0.006	-0.021	-0.033	-0.024	-0.014	-0.022	0.011	

27. Salinity Layering in the Southern Entrance

So far it has been assumed that a vertical column of water is completely mixed, but in the Southern Entrance in the summer months, mixing extends from the surface down to the thermocline only. Thus one would expect the reduction in salinity, due to the excess of rainfall over evaporation in these months, to be confined to the upper layer. As this is in agreement with observations, it seems very probable that the salinity layering, like the temperature layering, is produced *in situ*. The decrease in salinity above the thermocline will add to the effect of the increase in temperature in lowering the density, and thus increasing further the stability of the layering. Similarly, in autumn both the loss of heat and the loss of fresh water from the surface by evaporation increase the density and lead to the formation of convection currents which eventually break down the layering.

28. Variations in Incoming Atlantic Water

Since the water in the Irish Sea comes from the Atlantic Ocean, any variation in the salinity of the incoming water or in its rate of flow should appear in the salinity observed at Irish Sea stations. As mentioned in Chapter VI, earlier investigators tended to attribute nearly all seasonal and year-to-year changes in salinity to changes in the inflowing water.

By considering a simplified type problem, it can be shown that a simple harmonic seasonal variation in the mean rate of flow would give rise to a seasonal variation of salinity, having practically the same amplitude and phase at all positions in the Sea. The maximum salinity would occur three months after the rate of flow reached a maximum. A seasonal variation in the salinity of the incoming water (its rate of flow remaining constant), on the other hand, would cause a variation decreasing in amplitude and becoming later in phase as one went further from the entrance.

In parts of the Irish Sea, other than the Southern Entrance and coastal waters, the seasonal variation of salinity may be the resultant of several of the processes described above, and existing observations are inadequate to distinguish between them.

VI. NON-TIDAL CURRENTS

29. Current-Meter Measurements

The movements of water, particularly in the northern part of the Irish Sea, are dominated by strong tidal currents, the directions and speeds of which are known with some accuracy and are discussed in Chapter VIII (page 57). Knowledge of the residual, non-tidal drift, however, is much less certain. The only measurements by current-meter would appear to be those described by Proudman (1938(b)), which were obtained at the SKULMARTIN lightship, about 3.7 km. from the Irish coast in latitude $54^{\circ} 32' \text{N}$, longitude $5^{\circ} 26' \text{W}$. A Carruthers drift-meter was used, suspended at a depth varying between 14 m. and 19 m. below the surface in a depth of water averaging 30 m. From observations over a period of a year, from 19th March 1935, to 18th April 1936, the residual drift was found to average about 0.5 km./day towards the south-east. The monthly mean values nearly all showed a component towards the east, but the component in the north-south direction was oscillatory, reaching maximum values of about 3.5 km./day in either direction. The residual drift towards the south-east is probably an indication of a coastal current only, and in no way representative of the mean current across the North Channel which, on other grounds, is believed to be northwards.

30. Drift-Bottle Experiments

A number of drift-bottle experiments have been made in the Irish Sea from 1894 onwards, but most of the earlier trials were with unweighted bottles, floating with a considerable part above water and so under the direct influence of the wind. In most cases the bottles drifted northwards or north-eastwards from the point of release, as would be expected from the direction of the prevailing winds. Comparatively few bottles have found their way out of the Irish Sea through the North Channel, and there is no record of any bottle released in the Irish Sea having passed southwards out of the area.

The most extensive drift-bottle investigation was that carried out by Daniel (Daniel and Lewis 1929), who used bottles of the Ministry of Agriculture and Fisheries type, weighted to float with only a very small portion above the surface. The movement of these bottles should be independent of the direct force of the wind and give the drift of the surface layer of water which, however, will itself be determined largely by the wind. During the two years from June 1925 to June 1927, 12 bottles were released at monthly intervals from each of four stations on the Holyhead-Kingstown steamer route. Of the total of 1,180 bottles released, 596 were recovered, the great majority from the Irish Sea itself. Eighty-four passed through the North Channel and were recovered from the west coast of Scotland, the Orkneys and Shetlands, and, in one case, Norway. None of the bottles passed southwards through St. George's Channel. The majority of the landings were focused on the north-east boundary of the Irish Sea, i.e., on the coasts of south-west Scotland and north-west England. No significant difference was noted between the drift of bottles released from the different stations.

Daniel computed the residual winds for the periods corresponding to the drifts of the various groups of bottles, and found a good correlation between them both in direction and speed. If V is the mean speed of drift and W is the mean wind speed, the results were interpreted in terms of Witting's formula $V = MW^{\frac{1}{2}}$; M is a constant which Witting found to be 0.44 when V and W are in cm./sec. Daniel measured V and W in miles per day, and in these units Witting's value of M becomes 0.26. Assigning the landings of the drift bottles to four quadrants, Daniel found that for the north-east, north-west, and south-west quadrants the value of M averaged 0.20 to 0.26, but for the south-east quadrant M was 0.11. This result, combined with the observation that in the north-east quadrant the landings tended to be to the left of the residual wind, may be taken as evidence in support of a general northerly current, additional to the surface drift induced by the wind. This current was apparently weak enough to be stopped or reversed by persistent north winds.

Experiments with surface drift-bottles cannot be expected to give the general transport of water at all depths, but may give a useful indication of the direction and speed of movement of other drifting bodies. However, caution is needed in transferring drift-bottle results to movements of plankton, as pointed out by Johnstone (1929), since the physical nature of the plankton is different and often changes with time.

31. Knudsen's Estimate of the Mean Flow

One must look to indirect evidence for any further knowledge of the drift through the Irish Sea and this is found most clearly in the distribution of salinity (Fig. 8(a), page 30). The decrease of salinity from south to north and the curvature of the isohalines, convex northwards, implies a north-going drift, since the tendency of the run-off from the coasts and the excess of rainfall over evaporation over the sea is to reduce the salinity. This was very early recognized and Knudsen (1907) from considerations of continuity of salt and of water, estimated that the flow was such that the water in the Irish Sea would be completely renewed in a year at the longest. This implies an inflow at the rate of 0.27 km./day across the Southern Entrance and an outflow through the North Channel of 1.9 km. per day. Knudsen did not give any details of his computation.

32. Modification of Knudsen's Method

Recently, the calculation of the mean current by Knudsen's method has been repeated, with some modifications (Bowden, 1950). The Irish Sea was divided into three regions, separated by Sections (1) Cape Clear-Lands End, (2) Carnsore Point-St. Davids Head, (3) Dublin-Holyhead and (4) Skulmartin-Cardrain Point, as shown in Fig. 1 (page 6), and the equations of continuity of salt and of water applied to each region in turn. The run-off from the land was computed from the rainfall and the estimated loss, due mainly to evaporation. The rainfall and evaporation over the sea itself were computed similarly, and hence the net rate of addition of fresh water for each region as shown in Table 19 (page 50). Taking the Irish Sea as a whole, the mean current would appear to be approximately 0.21 km./day across the Southern Entrance and 1.55 km./day through the North Channel, i.e., only a little less than Knudsen's estimate.

When the regions are taken separately, however, there are large discrepancies between the values of the mean current across the common Sections (2) and (3), as estimated independently from Regions I and II, and II and III, respectively. One is forced to conclude that the process which was neglected in Knudsen's method, i.e., the transfer of salt across the sections by horizontal mixing, is comparable with the effects of transport by the mean current. Including mixing terms in the equations, however, renders them indeterminate without further data. On the assumption that transport by mixing across the Carnsore Point–St. Davids Head and Dublin–Holyhead sections is the same, since the courses of the isohalines are similar, the method is still applicable to the central region only. This gives the mean current across the Dublin–Holyhead section as 0.30 km./day which is less than one-third of the rate of 1.15 km./day which would be deduced from Knudsen's original estimate (Table 21). If this is substantially correct, it follows that there must be considerable transfer of salt by longitudinal mixing northwards across the Cape Clear–Lands End section and southwards through the North Channel.

TABLE 21

Mean Flow across Four Sections of the Irish Sea, as estimated by Knudsen's Method

<i>Across Section</i>	1. <i>Cape Clear –Lands End</i>	2. <i>Carnsore Pt. –St. Davids Hd.</i>	3. <i>Dublin –Holyhead</i>	4. <i>Skulmartin –Cardrain Pt.</i>
	<i>km./day</i>	<i>km./day</i>	<i>km./day</i>	<i>km./day</i>
Original Estimate (1907) ..	0.3	1.3	1.15	1.9
Revised Estimate (1950) ..	0.1	0.35	0.3	0.5

33. Deductions from Temperature and Salinity Distributions

Reverting to qualitative reasoning based on the distribution of temperature and salinity, Nielsen (1907) suggested a southward current through the Irish Sea as part of an anti-cyclonic circulation around Ireland, but his reasoning would appear to be doubtful. Other investigators have agreed that the general flow is northward, but have proposed modifications in detail. An early review by the Conseil International (1906–07) suggested a current flowing southwards near the Irish Coast, from the course of the isotherms. The evidence for the general northward flow was summarized by Bassett (1909) and, from the shapes of the isohalines and isotherms he concluded that, after passing northwards through the Dublin–Holyhead channel, the main flow turned eastwards and passed round the east side of the Isle of Man, instead of following the deeper channel to the west of it. This view was supported by Johnstone (1912), who adduced the results of drift-bottle experiments, the prevailing winds, and the implications of Ferrel's law in favour of it.

In the broad Southern Entrance the flow would appear to be complex. While Bassett (1909) interpreted the isohalines as indicating a large clockwise eddy off the entrance to the Bristol Channel, Matthews (1913), from his extensive observations of temperature and salinity between 1903 and 1912, concluded that the circulation was anti-clockwise, the most saline water entering between the Scillies and Lands End. Some of this water escapes from the circulation, passing northwards through St. George's Channel, and eventually leaves the Irish Sea through the North Channel, considerably diluted. The remainder of the water, however, turns westwards and southwards off the south coast of Ireland, and, somewhat diluted, rejoins the flow into the English Channel. This system of currents, according to Matthews, has a seasonal variation, the inflow of highly saline water from the Atlantic being strongest about February, while the outflow of diluted water from St. George's Channel is strongest in August.

34. Application of Helland-Hansen's Method

Harvey (1929) has applied Helland-Hansen's method of computing currents from the distribution of density to the waters south-east of Ireland. From observations taken in June–July, 1924, the mean density between the surface and a depth of 60 m. was calculated for a number of stations. These data enabled the difference between the current at the surface and at 60 m. to be estimated for several sections. Assuming that the main transport takes place in the layer above 60 m., the results were in agreement with Matthews's suggestion of an anti-clockwise circulation in the Southern Entrance to the Irish Sea. The speed of the water passing northwards through the Lands End–

Scillies channel was estimated to be about 2.5 km./day, and on the northern side of the eddy, south of St. George's Channel, the estimated speed in a north-westerly direction was about 1.25 km./day. However, as pointed out by Harvey, although the dynamical method of computing currents has proved very successful for currents in the open ocean, one meets with a number of difficulties when attempting to apply it to shallow and restricted waters. Among these are (a) the effect of tidal streams in causing periodic changes in the slope of the isobaric surfaces, (b) internal waves causing vertical oscillations of the surfaces of equal density, particularly where the thermocline is well developed, and (c) the effect of onshore or offshore winds in altering the slopes of the isobaric surfaces.

The salinity distribution shown in Fig. 8(a) (page 30) gives no indication of any eddy-like circulation in the Southern Entrance, but it should be remembered that this chart is based on mean values over a number of years, so that variations in distribution of a seasonal or temporary nature would be eliminated. As mentioned above, there would seem to be considerable mixing by horizontal turbulence in this region, which is consistent with the occurrence of large eddies of a non-permanent nature.

35. Year-to-Year Variations

The seasonal variation of salinity shows significant changes from year to year, and if salinity variations are attributed to variations in the inflow of Atlantic water, this flow itself must vary from year to year as well as from season to season. Bassett (1908) referred to the inflow of warm, saline Atlantic water as being strongest in spring and weakest in autumn to account for the spring maximum of salinity observed in the northern part of the Irish Sea, west of a line from Holyhead to the Calf of Man. In subsequent years he developed the idea that the year-to-year variations in the intensity of the salinity maximum were related to variations in the strength of the Gulf Stream system, and that it should be possible to forecast the weather to be expected in summer from salinity observations earlier in the year (Bassett, 1913). It has since been recognized (Johnstone, 1929) that, although some correlation may exist between the oceanic circulation in the eastern North Atlantic and the weather over the British Isles, salinity data from the Irish Sea alone would be totally inadequate for seasonal forecasting.

The view has been put forward (Bowden, 1950) that, just as the seasonal variation of salinity near the coasts is to be attributed to variations in run-off from the land, so the variations at open-sea stations are largely due to seasonal variations in rainfall, and, more particularly, evaporation over the sea itself. If this view is accepted, earlier investigators have probably over-estimated the effects of the inflowing drift of Atlantic water, and the above deductions as to its seasonal and year-to-year variations should be treated with reserve.

36. Correlation between Salinity Anomalies

The correlation between the salinity anomalies at a pair of stations for various time intervals was considered by Proudman (1940). For a station mid-way between Fishguard and Rosslare and a station mid-way between Dublin and Holyhead, the correlation was found to be a maximum for a time lag of $4\frac{1}{2}$ months. On the assumption that the maximum correlation coefficient indicates that the same water has passed from one station to the other in the corresponding interval, this gives an estimate of the steady drift in this region, which would be in agreement with Knudsen's original estimate. The anomalies were calculated from the annual means of salinity. There is, however, a significant seasonal variation of salinity at each of these two stations, with a phase difference of about 4 months, which may be due to causes other than the passage of the same body of water past the two stations. If anomalies from the monthly, instead of the annual, means are considered, as was done in Section 15 (page 44) the maximum correlation for a time interval of $4\frac{1}{2}$ months is absent, but a maximum occurs for a lag of 12 months, which would be consistent with the slower rate of flow, deduced from the revised application of Knudsen's method.

Knowledge of the mean flow through the Irish Sea is still far from being conclusive. A reliable estimate will probably not be attained until direct current-meter observations have been made in suitable positions, such as in the section between Dublin and Holyhead.

37. Theory of Cascading

Cooper and Vaux (1949) have drawn attention to a way in which conditions in the Celtic Sea, which includes the southern entrance to the Irish Sea, can affect Atlantic water beyond the continental shelf. Owing to winter cooling by back radiation and evaporation, water on the shallower parts of the continental shelf may acquire a higher density than in the surface layers over the continental slope. A bottom current of cold water may set in, flowing down the slope until it reaches a depth such that its density corresponds to that of the neighbouring oceanic water. This process has been termed "cascading," and one may expect the occurrence and intensity to depend on the severity of the winter.

Considering a number of particular years, Cooper and Vaux have found several winters in which the increase in density was great enough for cascading to have occurred. To show that it did occur, however, it is necessary to have evidence that water found at some considerable depth off the shelf was actually at the surface only a short time previously. The oxygen and pH determinations made in the "Armauer Hausen" in June 1914, provided such evidence by showing a layer of maximum O_2 content at 800 m. at a station near the slope. Since the temperature, salinity, and density of this water corresponded to that of the water in the western part of the Celtic Sea in the preceding January and April, this may be taken as evidence of cascading.

The loss of water by cascading requires a compensating inflow, and, after considering various possibilities, the most likely source appears to be a surface inflow of Atlantic or Bay of Biscay water from the south-west.

Although the process has been called "cascading", the water movements probably take place very slowly. It has not yet been found possible to investigate the process quantitatively, or to assess the relative importance of density differences and the surface stress of onshore winds, for example, in producing a vertical circulation of the water.

VII. CHEMICAL INVESTIGATIONS

Very few chemical investigations (apart from the determination of salinity) have been made in the Irish Sea. Holt (1901) collected samples from a number of stations in the Irish Sea and examined various chemical properties, including alkalinity and carbon dioxide in solution. In the light of later developments in technique, however, his work cannot be regarded as being more than exploratory.

Moore, Prideaux, and Herdman (1914) investigated the seasonal variation of hydrogen-ion concentration in samples taken in Port Erin Bay and at distances up to 5 miles out to sea. They found the pH value to be about 8.15 in winter, increasing in spring and reaching a maximum of about 8.4 in summer. The increase in pH in spring corresponds to a decrease in dissolved carbon dioxide, and they showed that it was related to the spring increase in photosynthetic activity. In general the pH tended to be higher close inshore than farther out to sea. The correlation between pH and photosynthesis was emphasized by experiments which they made in pond water, which had a much higher concentration of phyto-plankton than the open sea and in which the pH reached values as high as 9.0.

The seasonal variation in pH was confirmed by Bruce (1925), again working with samples from Port Erin Bay. He also found a tidal variation, of range pH 0.03, the higher value occurring on the ebb tide. A variation of this type is to be expected if photosynthetic activity is more intense in inshore water.

No investigations of phosphate, nitrate, or other chemical constituents appear to have been made in the Irish Sea.

VIII. TIDES AND TIDAL CURRENTS

38. Introduction

Because of the importance of tidal elevations and currents to navigation, much information concerning them has been collected. For detailed information, reference should be made to publications such as the *Admiralty Tide Tables* and *Atlas of Tidal Streams of the Waters Surrounding the British Islands*. The purpose of this account is to give a general survey of the distribution of tidal elevations and currents over the Irish Sea, and to point out any influences they may have on other oceanographical features.

To represent accurately the tidal elevations at a given place many harmonic constituents have to be considered. The following account is concerned almost entirely with the average semi-diurnal tide, as represented by the principal lunar constituent M_2 , having a period of 12 hr. 25 min. of solar time. If the principal solar constituent S_2 , with a period of 12 hr. solar time, is combined with M_2 , the average fortnightly alternation of spring and neap tides may be taken into account.

39. Observations

From tide-gauge observations at a coastal station, the average range of tide and the average time interval by which high water follows an upper or lower transit of the moon across the meridian of Greenwich may be determined. These two quantities are constants for a given place and have been found for many coastal stations. Away from the coasts, few attempts have been made to obtain direct observations of tidal elevations. On the other hand, many observations of tidal currents have been made and published by the Admiralty.

The currents and elevations are related to one another by well established dynamical principles. Thus from the coastal elevations and the currents at stations in the open sea, the distribution of elevations over the whole area of the sea may be computed.

40. Charts of Co-tidal and Co-range Lines

Figs. 13 and 14 (pages 59–60) show charts of co-tidal and co-range lines for the average semi-diurnal tide in the Irish Sea, as computed by Doodson and Corkan (1931). The time of high water, which is the same at all points on a given co-tidal line, is expressed in lunar hours after an upper or lower transit at the Greenwich meridian. Since the interval between two successive transits is divided into twelve lunar hours, one lunar hour is approximately 1 hr. 2 min. of solar time. Fig. 13 shows that across the Southern Entrance high water occurs at about $4\frac{1}{2}$ hr. lunar time, while in the North Channel high water occurs at 11 hr. lunar time, i.e., at nearly the same time as low water in the Southern Entrance. High water occurs within one hour of the same time over the whole of the northern part of the Irish Sea, from the Dublin-Holyhead line to the North Channel.

As shown by Fig. 14, the range of tide is, in general, greater on the east side of the Irish Sea than on the west side. The smallest ranges, less than 4 ft., occur on the southern part of the east coast of Ireland and at the northern end of the North Channel. The largest ranges occur in the upper part of the Bristol Channel (more than 24 ft.) and on the coast of north-west England, particularly in Morecambe Bay and Liverpool Bay (20 ft). To obtain the range at spring tides, the average range must be multiplied by a factor which depends on the ratio of the amplitudes of the S_2 and M_2 constituents. This factor changes gradually with the geographical position. Some values, typical of the locality of the port, are given in Table 22.

TABLE 22
Ratio of Spring Range to Average Range of Tide

Place	Spring Range Average range	Place	Spring Range Average range
Belfast	1.25	Port William (Luce Bay)	1.32
Kingstown (Dun Laoghaire) ..	1.29	Silloth	1.32
Rosslare	1.47	Whitehaven	1.30
Waterford Harbour	1.32	Liverpool	1.32
Queenstown (Cobh)	1.31	Holyhead	1.36
Douglas	1.33	Pembroke Dock	1.37
		Swansea	1.35
		Bristol (King Road)	1.35



Ordnance Survey

13. Irish Sea : co-tidal lines—average time of high water in lunar hours after moon's transit at the meridian of Greenwich. (Based on Admiralty Chart No. 301.)



14. Irish Sea : co-range lines—average range of tide in feet
(Based on Admiralty Chart No. 301.)

41. Charts Relating to Tidal Currents

Figs. 15, 16 and 17 (pages 62–64) give charts showing the direction of the maximum flood streams, the amplitude of the current at spring tides, and the lunar time at which the flood current reaches its maximum rate, respectively. They are based on data given in the Admiralty publication *Atlas of Tidal Streams of the Waters Surrounding the British Islands*, Parts I and II (1st and 2nd editions). The factor relating the spring rate to the average rate may be taken as the same as that given in Table 22 (page 58), for the ratio of spring range to average range for places in the same locality. It should be stressed that, while these charts give the general conditions in the open sea, no attempt has been made to show details of the currents near the coasts. The local variations are often very great, the currents tending to be stronger off salient points of the coastline and weaker in the intervening bays, while local eddies may occur near features obstructing the general flow.

A chart showing flood stream-lines for the northern part of the Irish Sea was first given by Beechey (1848). Stream-lines have not been drawn in Fig. 15, but the general directions of the flood streams are shown by the arrows. The flood streams flow into the Irish Sea from both the Southern Entrance and the North Channel and follow the general directions of the coastlines. Fig. 17 shows that the flood current reaches its maximum at about $3\frac{1}{2}$ hr. lunar time across the Southern Entrance and the entrance to the Bristol Channel. Approaching the entrance to St. George's Channel, the phase of the current rapidly becomes later, and between Carnsore Point and St. Davids Head maximum flood occurs at about 7 hr. lunar time. Further north the phase changes slowly, and the time of maximum flood is practically constant at about 8 hr. lunar time over the whole of the northern part of the Irish Sea, north of the Dublin–Holyhead line. Currents flow into this area, therefore, simultaneously from the north and the south. The flow southwards through the North Channel divides north of the Isle of Man, part continuing southwards and part turning eastwards into the north-eastern part of the area. Similarly, the flow across the Dublin–Holyhead line divides south of the Isle of Man, part continuing northwards and the other part turning eastwards into the eastern part of the area. In the regions west and east of the Isle of Man, where the streams from north and south meet, the currents are necessarily small.

Tidal currents are seldom strictly rectilinear, the velocity vector actually tracing out an ellipse during the tidal period. In most parts of the Irish Sea, however, the ratio of the minor axis to the major axis of the ellipse is small and does not exceed 0.1. The main exception is in the south-east part of the Southern Entrance, particularly in the region of Lands End and the Scilly Isles, where the ratio exceeds 0.5 in some positions. In other places where the currents are rotatory to an appreciable extent, such as off the coast of north-west England from St. Bees Head to Walney Island, the currents are generally weak.

Comparing the phases of the currents (Fig. 17, page 64) and the elevations (Fig. 13, page 59), it is seen that in the Southern Entrance maximum flood occurs about one hour before high water. This difference diminishes northwards, and in the entrance to St. George's Channel the flood current reaches its maximum almost simultaneously with high water. This corresponds to the theoretical relation for a progressive wave. In St. George's Channel, however, the phase of the current changes only slowly compared with that of the elevation, so that north of the Dublin–Holyhead line, the flood current reaches its maximum between $2\frac{1}{2}$ and 3 lunar hours before high water. This is approximately the relation to be expected for a standing oscillation in the northern part of the Irish Sea.

From Fig. 16 (page 63), the amplitudes of the tidal currents are small (less than 1 kt. at springs) across the Southern Entrance, but large (about 4 kt.) in the North Channel. The currents are also strong in the upper part of the Bristol Channel, on the western side of St. George's Channel, and between south-west Scotland and the northern end of the Isle of Man. They are very weak in an area extending westwards and south-westwards from the Isle of Man towards the Irish coast. The areas where strong currents occur off south-east Ireland and in the North Channel correspond to areas with a small range of tidal elevation.

42. Dynamical Explanation

The tidal elevations and currents in the northern part of the Irish Sea, bounded by lines from Donaghadee to Portpatrick (across the North Channel) and from Dublin to Holyhead, may be accounted for quite closely in terms of a standing oscillation, as shown by Proudman and Doodson

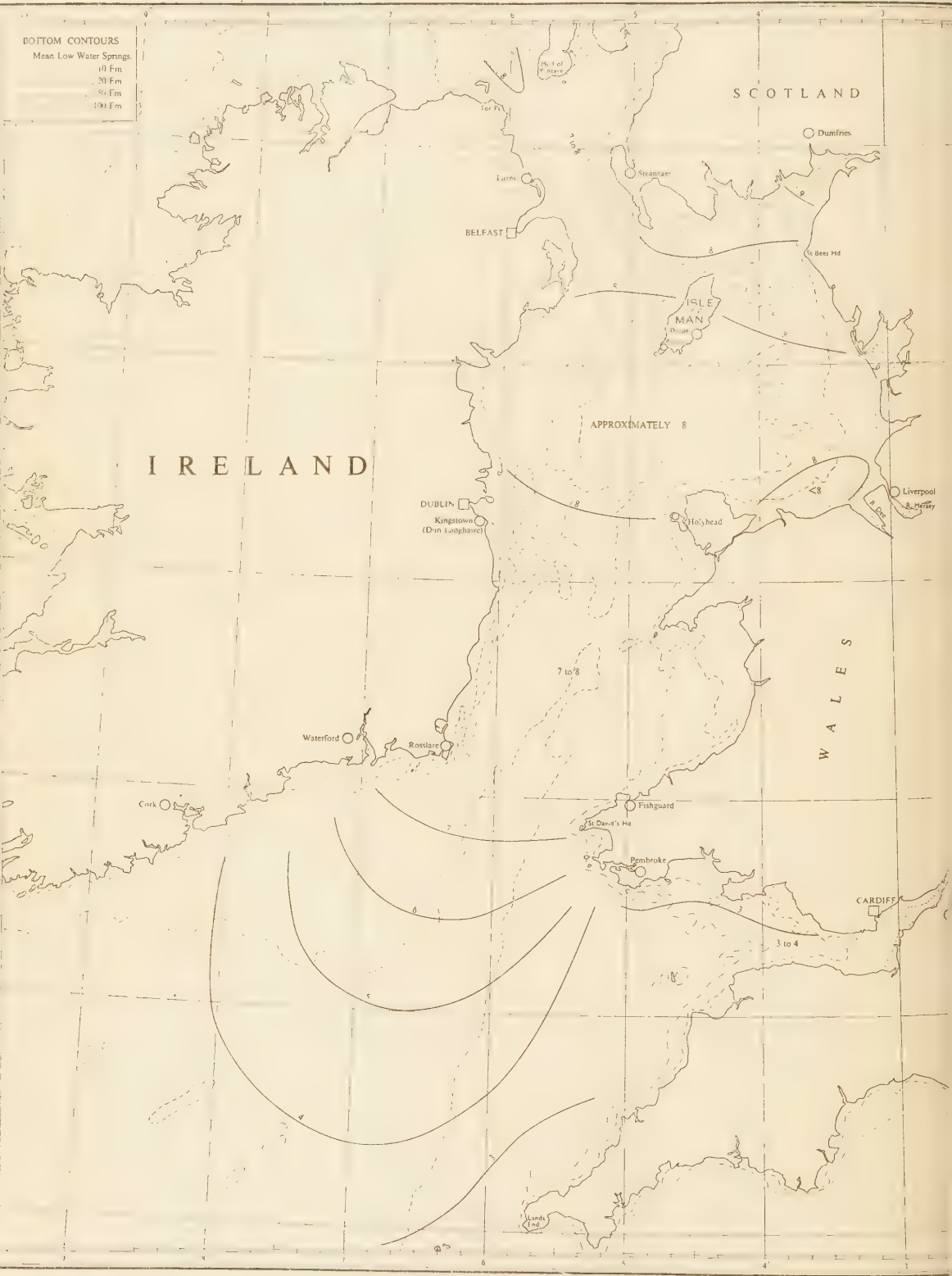


15. Irish Sea : direction of maximum flood streams



Ordnance Survey 1953.

16. Irish Sea : amplitude of tidal currents at springs, in knots



17. Irish Sea : Lunar time of maximum flood streams
in lunar hours after moon's transit at the meridian of Greenwich

(1923). Currents flow into this area almost simultaneously from north and south, reaching their maximum rate at 7 hr. 50 min. lunar time. Neglecting the effects of the earth's rotation and friction, high water should occur simultaneously over the whole area 3 lunar hours later, i.e., at 10 hr. 50 min. lunar time. Taking into account the relation between surface gradients and accelerations, the range should increase from about 10 ft. near the open ends of the area to about 18 ft. near the coast of north-west England, the co-range lines being perpendicular to the flood lines.

If the earth's rotation is allowed for, however, secondary gradients would be set up, perpendicular to the flood lines and reaching their maximum values at the times of maximum current. The retarding effect of friction, also being greatest when the currents are at a maximum, introduces gradients in the direction of the flood lines at the same time. The combined effect of the earth's rotation and friction on the range is very small, and the co-range lines remain almost perpendicular to the flood lines. The main effect on the time of high water is to make it occur rather earlier than 10 hr. 50 min. on the coast of North Wales, and rather later on the south coast of Scotland. The effects are comparatively small, however, and the time of high water at all places in the area is between 10 and 11 hr. lunar time. The effect of the earth's rotation on the currents is to cause small secondary currents to flow transverse to the main flood lines, reaching their maximum values about the time of high water, while the effect of friction on the primary currents causes maximum flood to occur rather less than 3 lunar hours before high water.

43. Influence of Tidal Currents on Temperature and Salinity

The areas of weak tidal currents shown in Fig. 16, i.e., the Southern Entrance and the area extending westwards and south-westwards from the Isle of Man towards the Irish coast, are those in which layering of temperature and salinity occurs in the summer months, as described in Section 4 (page 22). In deep water the formation of a thermocline during the summer months is quite normal. The surface layer is well mixed, due to turbulence set up by wave motion and wind currents, but these effects diminish rapidly with increasing depth, and below a certain depth the turbulence is insufficient to cause thorough vertical mixing. Where strong tidal currents occur in shallow water, however, there will be produced considerable turbulence which, presumably, will be most strongly developed in a layer near the bottom, where the shearing stresses are greatest. Under such conditions, the turbulent mixing at all depths may be sufficient to prevent the formation of a thermocline.

Considering conditions in the English Channel, Dietrich (1950) found that the areas where a thermocline develops in summer correspond to those where the amplitude of the tidal currents does not exceed about 2 kt. at springs. This criterion would appear to be applicable also to the Irish Sea. One might expect the criterion to depend on the depth as well as on the amplitude of the currents. The figure of 2 kt. may be appropriate to the average depths in the English Channel and Irish Sea, whereas in deeper water stronger tidal currents might be needed to prevent the formation of a thermocline.

It is probable that tidal currents also increase turbulent mixing in the horizontal plane, and so promote the interchange of heat or salt content between coastal water and the centre of a channel. These processes have been considered in Sections 20 (page 48) and 24 (page 50). The effects of tidal currents in causing variations of temperature and salinity, with the tidal period, at a fixed station, due to the bodily movements of water masses, have also been considered earlier in Sections 7 (page 24) and 14 (page 44).

IX. SUMMARY

The present paper is a survey of work which has been done on the Physical Oceanography of the Irish Sea since the year 1900.

The distribution of the temperature and salinity of the surface water is shown by a series of charts, giving mean values for the year as a whole and for the months of February, May, August, and November. For the Southern Entrance, where considerable changes of temperature and salinity with depth occur at some seasons, corresponding charts of mean values for the bottom water are also given. The distribution of these two properties is demonstrated further by tables of monthly mean values at a number of representative stations.

Besides the seasonal changes, variations of temperature with diurnal and tidal periods, and the irregular fluctuations which occur from month to month and from year to year are discussed.

The physical processes affecting the temperature and salinity, such as the exchange of heat energy and water vapour between the sea and the atmosphere, and turbulent mixing in the sea, are described in relation to conditions in the Irish Sea.

Evidence for the non-tidal flow of water through the region comes partly from drift-bottle experiments and partly from deductions based on the distribution of temperature and salinity. In discussing the estimates obtained by the latter method, stress is placed on the importance of taking account of horizontal mixing, both laterally, and along the direction of flow.

A general account is given of the distribution of tides and tidal currents throughout the sea, illustrated by charts showing the co-tidal and co-range lines, and the amplitudes and phases of the tidal currents. The effects of tidal mixing on the distribution of temperature and salinity are indicated.

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